

A CAPILLARY VISCOMETER FOR
NON-NEWTONIAN LIQUIDS

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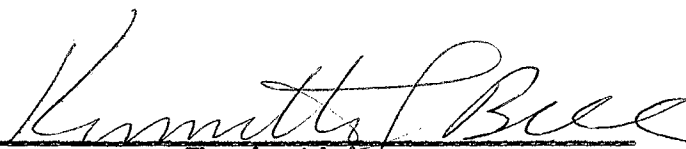
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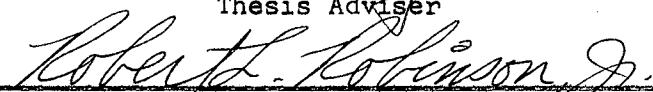
$\{f_{\alpha} : \alpha \in \mathcal{A}\} \subseteq \mathcal{F}$ is a \mathcal{F} -maximal family of functions

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Thesis Approved:



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PREFACE

The chemical engineer is frequently concerned with fairly viscous liquids whose flow pattern is usually laminar. The processing of emulsions, slurries, polymeric melts, polymer solutions, and dispersions is of continually increasing industrial importance. Many of these liquids behave differently from an ideal Newtonian liquid such as water. These fluids are characterized by a nonlinear shear stress-shear rate relationship. Extrapolation of these relationships is risky, and extended experimentally determined curves are advisable for use in design work.

A capillary viscometer was designed and calibrated for obtaining accurate flow curves for any time-independent fluid of interest. Data taking was limited to calibration fluids and solutions of sodium carboxymethylcellulose (CMC). Design details, operating procedure, and results of experimental runs are presented in this thesis.

Many individuals have given me assistance and advice during the course of this project. I am indebted to Dr. Kenneth J. Bell, my adviser, for his helpful suggestions in relation to this study. Mr. Don Adams and Mr. Kohei Ishihara provided me with prepared samples of CMC run through their equipment and gave me much useful advice. Professor George G. Smith and Messrs. Preston Wilson and Gene E. McCroskey gave much aid in the construction of the apparatus. I also wish to thank my wife, Mary, and my father who gave me much encouragement.

I am indebted to the United States Air Force Institute of Technology for the opportunity to undertake graduate work including this thesis study. I am also indebted to the Monsanto Company which provided the funds for purchasing the necessary equipment. I further wish to thank the Phillips Petroleum Company, Research Division, Bartlesville, Oklahoma, for furnishing two secondary viscosity standards, KC 10 and KC 20 Oils. I also wish to thank the Hercules Powder Company for furnishing the carboxymethylcellulose powder used in making test solutions.

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CHAPTER I

INTRODUCTION

The measurement of viscosity is of considerable importance in both industrial production and fundamental science. Viscosity is the quantity that determines the forces to be overcome when fluids are used in pipelines, heat exchangers, bearings, etc., and it controls the flow of liquid in such processes as spraying, extrusion, surface coating, injection moulding, and other diverse applications.

This study is concerned only with laminar flow of time-independent fluids, although it should be noted that turbulent flow can be obtained in the designed apparatus in some instances.

The following goals were set for this project:

1. Design and build a reliable capillary viscometer to obtain accurate apparent viscosities at temperatures and shear rates of interest.
2. Calibrate the experimental apparatus using distilled water and standard viscosity oils.
3. Using the calibrated apparatus, obtain flow and viscosity data for carboxymethylcellulose (CMC) solutions of various concentrations and shear histories at several temperatures of interest.
4. Compare shear stress-shear rate data from the capillary viscometer with data taken with the Fann VG model 35 rotational

viscometer.

All four goals were achieved.

CHAPTER II

FUNDAMENTAL CONCEPTS

Newtonian Fluid Characteristics

Newtonian laminar flow is defined by Newton's equation which states that viscosity, μ , is equal to the ratio of shear stress to shear rate and is constant for a Newtonian fluid at a particular temperature and pressure.

$$\begin{array}{l} \mu \\ \text{(constant)} \end{array} = \tau / (dv/dr) . \quad (1)$$

The shear stress, τ , which acts throughout the liquid, is defined as the applied shearing force divided by the area over which it acts. Common units are either dynes/cm² or lb_f/ft². The shear rate, dv/dr , is defined as the differential change in velocity of the fluid, v , to the differential change in the distance, r , measured perpendicular to the direction of shear. Since shear rate is a velocity divided by a length, it has the dimension of (time)⁻¹. The common unit is the reciprocal second, denoted by sec⁻¹.

For streamline flow in a cylindrical capillary (Figure 1) of radius R and length L with a pressure difference ΔP between the ends, the shear rate is $-dv/dr$, where v is the velocity of the liquid at a distance r from the axis of the capillary. The negative sign simply shows that shear rate terms are negative if distance r is measured from the center

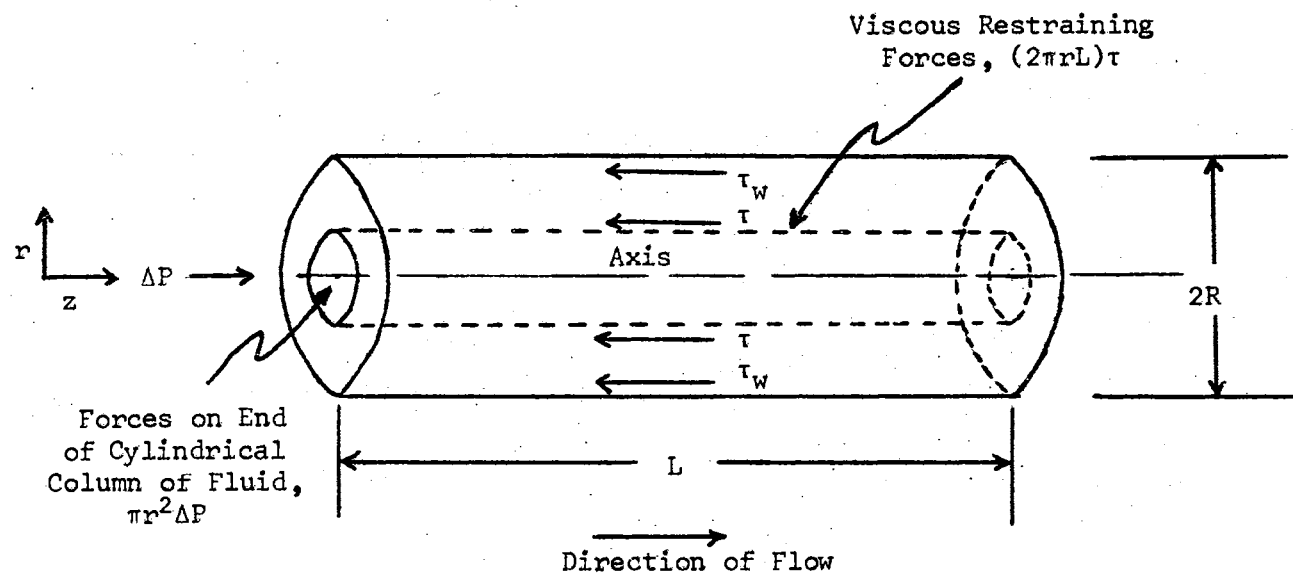


Figure 1. Force Balance on a Column of Fluid Flowing Through a Capillary Tube

line of the tube, as is usually the case. The shear stress is obtained by assuming no acceleration of the liquid and making a force balance on the cylindrical element of length L and radius r . The force acting in the direction of motion due to applied pressure is $\pi r^2 \Delta P$. The force due to viscous resistance of the surrounding liquid is $2\pi r L \tau$. These forces must balance; therefore,

$$\tau = \Delta P r / 2L \quad (2)$$

and

$$\tau_w = \Delta P R / 2L \quad (3)$$

For Newtonian behavior, substituting into Equation 1

$$dv/dr = \Delta P r / 2\mu L \quad (4)$$

Assuming that there is no slip of the fluid at the capillary wall, Equation 4 is integrated and the boundary condition that the velocity is zero at $r = R$ is applied to give

$$v = \Delta P (R^2 - r^2) / 4\mu L \quad (5)$$

Thus, Newtonian fluids have a characteristic parabolic velocity distribution across the capillary.

The volume of liquid flowing in unit time between r and $r + dr$ is $2\pi r v dr$, and therefore the overall volumetric flow rate Q through the capillary is given by

$$Q = \int_0^R 2\pi r v dr \quad (6)$$

Substituting Equation 5 into Equation 6 and integrating

$$Q = \pi \Delta P R^4 / 8 \mu L \quad . \quad (7)$$

This is the familiar Poiseuille equation deduced in 1840 and is quite rigorous for Newtonian fluids.

Non-Newtonian Fluid Characteristics

Relatively few liquids behave according to Equations 1 and 7. Examples are water, simple organic liquids, dilute solutions, and gases. Most other fluids are classified as "non-Newtonian" since Equation 1 does not hold and the ratio of shear stress to shear rate is not an exact proportionality. Therefore, viscosity is not a unique quantity in this case, but one that varies in value with the rate of shear at which it is measured. The term apparent viscosity, μ_a , has been much used in connection with non-Newtonian fluids and will be used in this thesis. It is defined for any single measurement as the ratio of shear stress to true shear rate. It is obvious that a single-point measurement on a non-Newtonian fluid is completely inadequate for characterizing its flow behavior. Many points are usually necessary to obtain completely reliable flow curves.

Non-Newtonian fluids have been broken down into several types as shown in Figure 2 according to the relationship between shear stress and shear rate. If a straight line is obtained passing through the origin, the fluid is Newtonian and the slope of the line is the Newtonian viscosity. If a straight line is obtained, however, which does not pass through the origin but intersects the shear stress axis at a fixed point, the fluid is a Bingham plastic. The point at which the axis is intersected is known as the yield stress, τ_y , which is the

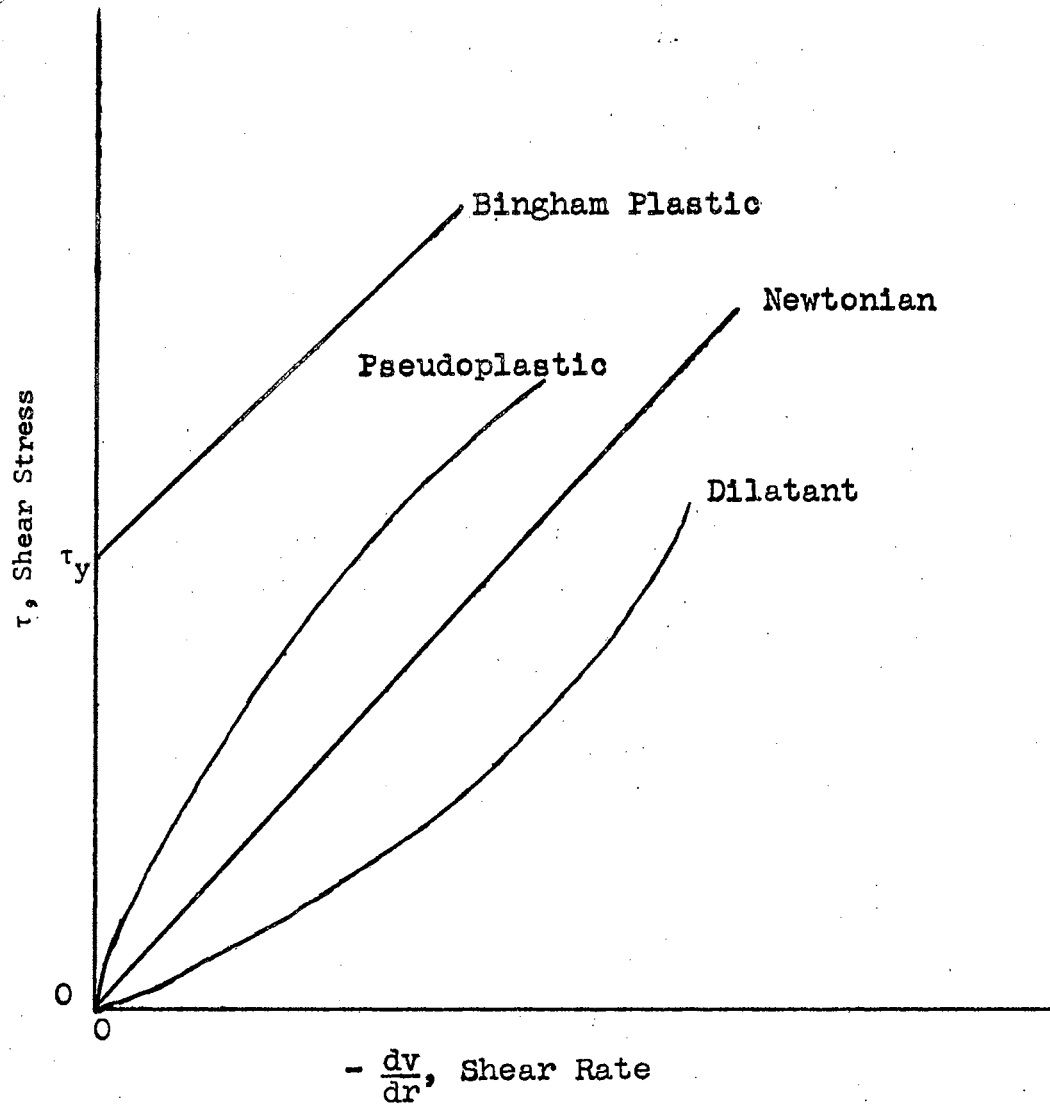


Figure 2. Shear Stress-Shear Rate Diagram

initial shear stress that must be exerted on the fluid to make it flow. This class of fluid can usually be characterized by the following equation:

$$\tau - \tau_y = \mu_p (dv/dr) \quad (8)$$

The term, μ_p , is called the plastic viscosity and is the slope of the straight line for a Bingham plastic.

A pseudoplastic fluid has a curve concave to the shear rate axis and hence apparent viscosity decreases with increasing shear rate. A dilatant fluid has a curve convex to the shear rate axis and apparent viscosity increases with increasing shear rate. Both of these type of fluids can often be represented by the following equation known as the power law, which was originally proposed by Ostwald:

$$\tau = k (dv/dr)^n \quad (9)$$

The constant n is called the power law index and shows the deviation of the fluid from Newtonian behavior. For n less than a value of 1.0, the fluid is pseudoplastic; and for n greater than a value of 1.0, the fluid is dilatant. The constant k is an index of the consistency of the fluid. The higher k , the more viscous the fluid. Thus, fluids can have the same value of n and still vary widely in consistency.

To derive an expression for the velocity distribution of power law fluids in general, we start with

$$-dv/dr = f(\tau) \quad (10)$$

From Equations 2 and 3,

$$\tau/\tau_w = r/R \quad (11)$$

and from Equations 10 and 11,

$$-dv/dr = f(\tau_w r/R) . \quad (12)$$

From Equation 6

$$Q = \pi \int_0^R v d(r^2) . \quad (13)$$

Integrating by parts and substituting Equation 12

$$Q = [\pi r^2 v]_0^R + \pi \int_0^R r^2 f(\tau_w r/R) dr . \quad (14)$$

The first term is zero since $v = 0$ at $r = R$, and the following equation can be obtained by substitution and rearrangement:

$$Q/\pi R^3 = 1/\tau_w^3 \int_0^{\tau_w} \tau^2 f(\tau) d\tau . \quad (15)$$

For a power law fluid,

$$f(\tau) = (\tau/k)^{1/n} . \quad (16)$$

Substituting Equation 16 into Equation 15

$$Q/\pi R^3 = 1/k^{1/n} \tau_w^3 \int_0^{\tau_w} \tau^{2+1/n} d\tau . \quad (17)$$

Integrating and substituting Equation 2

$$Q = n\pi R^3 / (3n + 1) (R\Delta P / 2Lk)^{1/n} . \quad (18)$$

For a Newtonian fluid, $n = 1$ and $k = \mu$, and Equation 18 reduces to

Equation 7, the Poiseuille equation. If the power law is substituted into Equation 2, rearranged, and then integrated

$$\begin{aligned}
 v &= (\Delta P / 2Lk)^{1/n} \int_r^R r^{1/n} dr \\
 &= (n/n + 1) (\Delta P / 2Lk)^{1/n} (R^{(1/n)+1} - r^{(1/n)+1}) \quad (19)
 \end{aligned}$$

Substituting for the mean velocity, $v_m = Q/\pi R^2$, in Equation 18 and combining with Equation 19 and rearranging gives

$$v = v_m \left[(3n + 1)/(n + 1) \right] \left(1 - (r/R)^{(n+1)/n} \right) \quad (20)$$

This equation gives the velocity of the power law fluid as a function of the power law index n and the ratio of any chosen radius r to the radius of the tube R . Figure 3 shows typical velocity profiles plotted from Equation 20 for different values of n . For $n = 1$, the familiar parabolic profile of a Newtonian fluid is obtained. For n less than 1.0, the fluid is pseudoplastic; and as n approaches zero, flow approaches plug flow or infinite pseudoplasticity. For n greater than 1.0, the fluid is dilatant; and as n approaches infinity, the velocity profile assumes a conical shape.

In actuality, the behavior of most fluids is not as sharply defined as just presented but is usually a combination of several of the standard types over a wide range of shear rates. Two complications should be mentioned which make even more types of non-Newtonian fluids possible. They are time-dependency and viscoelasticity. For time-dependent fluids, the apparent viscosity depends upon the length of time during which the fluid has been sheared; i.e., the shear stress history of the

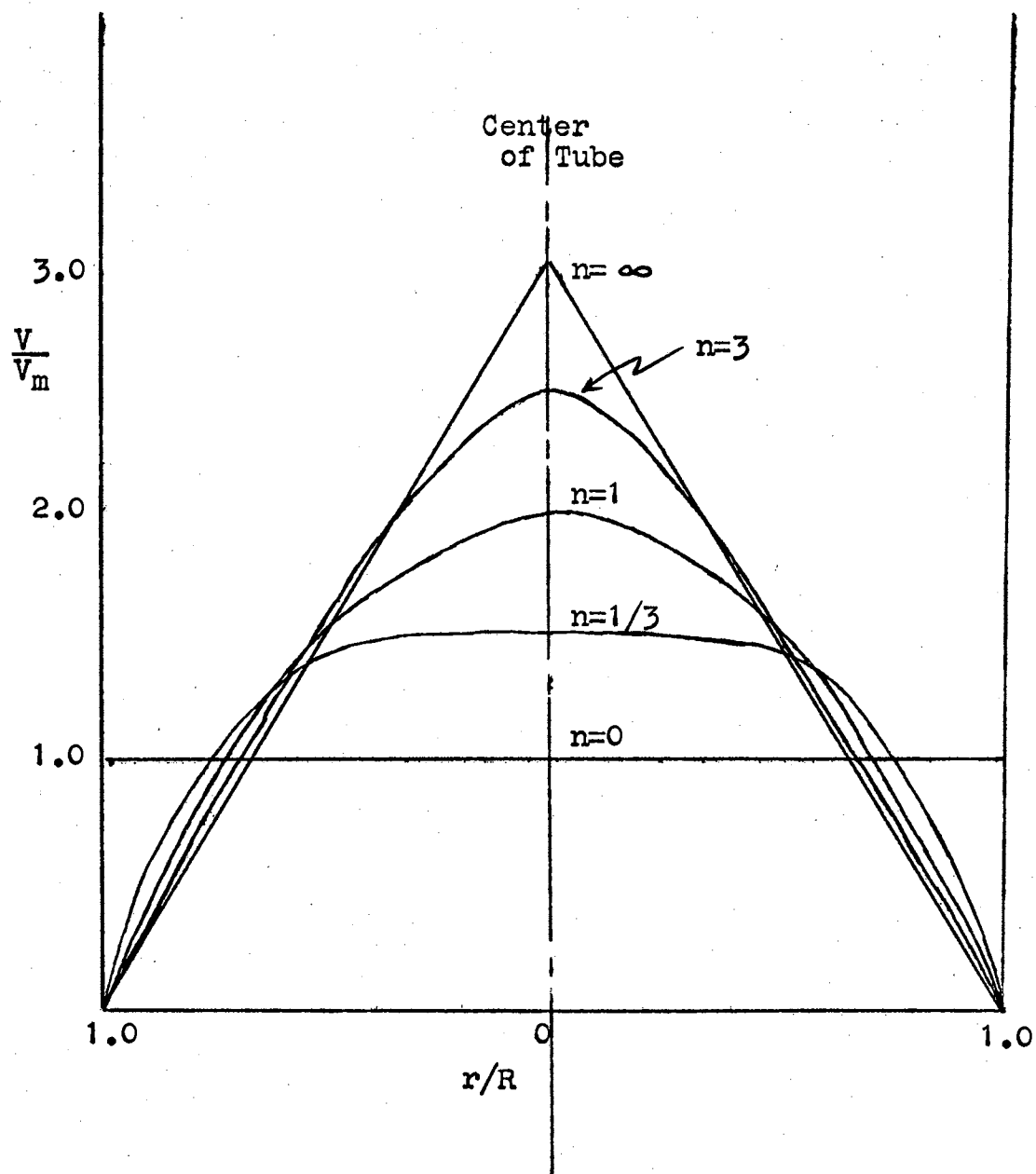


Figure 3. Fluid Velocity Profiles Using the Power-Law Index, n , for Comparison

fluid. There are two general types of time-dependent fluids. Thixotropic fluids show a decrease in apparent viscosity with time of shear, while rheopectic fluids show an increase in apparent viscosity with time of shear. Viscoelastic fluids exhibit elastic properties as well as viscous properties. The energy applied to such a fluid is partially stored as potential energy in addition to being dissipated as heat by the viscous forces. These complications are not treated in this study, but ways of handling them are available in the literature (20).

CHAPTER III

LITERATURE SURVEY

General Fluid Characterization

Rabinowitsch (18) in 1929 developed an expression for shear rate at a tube wall of a time-independent fluid in laminar flow which is entirely independent of the fluid properties. A complete development of this equation was also made by Mooney (16) in 1931. The equation is

$$(-dv/dr)_w = 3 (8Q/\pi D^3) + D\Delta P/4L \frac{d (8Q/\pi D^3)}{d (D\Delta P/4L)} . \quad (21)$$

In 1955 Metzner and Reed (14) rearranged this original equation into a more useful form by the following procedure: The mean velocity v_m is substituted for $4Q/\pi D^2$ in Equation 21 and rearrangement gives

$$(-dv/dr)_w = 3/4 (8v_m/D) + 1/4 (8v_m/D) \frac{d \ln (8v_m/D)}{d \ln (D\Delta P/4L)} . \quad (22)$$

By defining

$$n' = \frac{d \ln (D\Delta P/4L)}{d \ln (8v_m/D)} , \quad (23)$$

then Equation 22 becomes

$$(-dv/dr)_w = \frac{3n' + 1}{4n'} (8v_m/D) = \frac{3n' + 1}{4n'} (32Q/\pi D^3) . \quad (24)$$

This is a general correlation as has been shown by Metzner (13) and is

applicable to all time-independent fluids and not merely power law fluids. The derivation assumes that there is no slip at the tube wall and that viscoelastic effects are negligible. The assumption of no slip at the wall is not always valid for non-Newtonian fluids, and rate of shear may not be a unique function of the shear stress since the wall tends to introduce a preferred orientation. Oldroyd (17) has presented an approach to determine the effective slip at the wall; however, the no-slip condition is assumed for the work contained in this study.

In Equation 24 the derivative n' represents the slope of a logarithmic plot of $\Delta P/4L$ versus $32Q/\pi D^3$ (or $8v_m/D$). These plots are not true shear rate-shear stress diagrams and are called flow curves. It is much easier from a calculational viewpoint to work with n' than the derivative in Equation 21. The quantity n' is known as the "flow behavior index."

Integrating Equation 23 over any range of shear stresses for which n' may be considered constant, the following equation is obtained:

$$\frac{\Delta P}{4L} = k' (32Q/\pi D^3)^{n'} \quad (25)$$

where k' is also a constant. Equation 25 represents the tangent to the logarithmic plot of $\Delta P/4L$ versus $32Q/\pi D^3$ at a particular value of $\Delta P/4L$. In Equation 25, the quantity k' represents the value of $\Delta P/4L$ at a $32Q/\pi D^3$ value of unity on the plot. Actually, k' and n' are not true constants over the entire range of $32Q/\pi D^3$ for all fluids, and they are not assumed constant in the derivation. However, they are nearly constant in many instances, especially if the range of $32Q/\pi D^3$ or $\Delta P/4L$ taken is small. In the general case, different values of k' and

n' would have to be used for every value of $32Q/\pi D^3$, and Equation 25 would represent the tangent to the curve at a single point.

It can be noted that Equations 25 and 9, the power law equation, are very similar in appearance. If logarithms are taken of Equation 7 assuming n and k to be constant over at least a differential range of shear rates and stresses,

$$\ln \tau = \ln k + n \ln (-dv/dr) \quad (26)$$

Differentiating Equation 26, the definition of n , the power law index is obtained

$$n = \frac{d (\ln \tau)}{d (\ln (-dv/dr))} \quad (27)$$

Comparison of Equations 27 and 23 shows the difference between n and n' : n is the slope of a logarithmic plot of shear stress τ versus the corresponding shear rate $(-dv/dr)$, and n' is the slope of a logarithmic plot of shear stress at the wall of a round tube τ_w versus $32Q/\pi D^3$. In general, except for a Newtonian fluid, the shear rate at the wall at any given value of the wall shear stress is not equal to $32Q/\pi D^3$ as shown by Equation 24.

The relation between n and n' at any particular shear stress may be derived by taking logarithms of Equation 24, differentiating, and dividing by $d (\ln \tau_w)$.

$$\frac{d (\ln (-dv/dr)_w)}{d (\ln \tau_w)} = \frac{d \ln \frac{32Q}{\pi D^3}}{d (\ln \tau_w)} + \frac{d (\ln \frac{3n' + 1}{4n'})}{d (\ln \tau_w)} \quad (28)$$

Noting that the first two terms of Equation 28 also appear in Equations 23 and 27, it can be rewritten

$$1/n = 1/n' + \frac{d (\ln (3n' + 1/4n'))}{d (\ln \tau_w)} \quad (29)$$

Rearranging gives

$$n = \frac{n'}{1 - 1/3n' + 1 (dn'/d \ln \tau)} \quad (30)$$

The derivative in Equation 30 represents the slope of a plot of n' versus $\ln \tau$. If n' does not vary with shear stress, that is if the initial $\ln \tau_w$ versus $\ln 32Q/\pi D^3$ plot is essentially a straight line, the second term of the denominator is zero and n equals n' . In the general case, this will not occur and n and n' will be different. Although n may always be determined from n' , n' cannot be determined from n except in the special case of $n' = n = \text{constant}$. Thus, capillary viscometer data used to determine n' also are used to calculate the true shear stress-shear rate curves for a given fluid. However, if the data are obtained on a rotational viscometer, it is not generally possible to calculate the pressure drop-flow rate relationships directly and completely rigorously except by multiple integrations. Therefore, capillary viscometers have an inherent advantage over rotational viscometers if the data are to be used for pipeline design.

A relation may also be derived between k and k' . By rearranging Equation 18, the following equation is obtained:

$$\Delta P/4L = k \left(\frac{3n + 1}{4n} \right)^n (32Q/\pi D^3)^n \quad (31)$$

Comparing Equation 31 to Equation 25,

$$k' = k \left(\frac{3n + 1}{4n} \right)^n \quad (32)$$

When $n = 1$, $k = k'$, and the fluid is Newtonian. Usually k and k' are

different, however.

Metzner and Reed next obtained a generalized Reynolds number by first substituting the relationship for $\Delta P/4L$ in Equation 25 into the following definition of the Fanning friction factor:

$$f = (\Delta P/4L)/(\rho V^2/2g_c) \quad (33)$$

This gives

$$f = \frac{16\gamma}{D^{n'} V^{2-n'} \rho} \quad (34)$$

where γ is defined by

$$\gamma = g_c k' 8^{n'-1} \quad (35)$$

By letting $f = 16/Re$ as for Newtonian fluids in laminar flow, the Metzner-Reed generalized Reynolds number is

$$Re = \frac{D^{n'} V^{2-n'} \rho}{\gamma} \quad (36)$$

This development is completely rigorous and may be used to check the accuracy of experimental data. If perfect coincidence with the $f = 16/Re$ line is not obtained in the laminar-flow region, either the data or calculations are in error or the fluid exhibits thixotropic or rheo-pectic behavior.

Weltmann (21) has proposed a slightly different correlation approach by defining a Reynolds number dependent on the type of fluid. For power law fluids, she replaces the Newtonian viscosity μ by apparent μ_a where

$$\mu_a = g_c \tau / (-dv/dr) \quad (37)$$

Thus

$$Re' = DV\rho/\mu_a \quad (38)$$

For a Bingham plastic, μ_p would be substituted for μ .

For the case where $n' = n$, Equation 36 reduces to

$$Re = \frac{D^n v^{2-n} \rho}{g_c 8^{n-1} k \left(\frac{3n+1}{4n} \right)^n} \quad (39)$$

Upon substituting Equations 9 and 37 into Equation 39 and rearranging

$$Re = Re' \left(\frac{4n}{3n+1} \right) \quad (40)$$

Thus Weltmann's Reynolds number is identical to that of Metzner-Reed except for a multiplying factor if the fluid has a fixed and constant value of the power law index n .

In this thesis both γ , known as a generalized viscosity coefficient, and μ_a are determined for all fluids run. However, for CMC solutions, the condition $n' = n = \text{constant}$ does not hold. The quantities n' and n are usually close in value but neither is constant and both change significantly over different ranges of $32Q/\pi D^3$ and shear rate, respectively. Thus, γ should be used in preference to μ_a in this case since it is more rigorous for a general fluid.

Sources of Error and Their Correction

In the preceding section several equations for interpreting data were discussed. However, in using these equations, it is necessary to first correct for errors of measurement.

When a fluid stream discharges with high speed from the capillary of the viscometer directly into air, the stream carries an appreciable amount of kinetic energy. This kinetic energy may represent a significant part of the total applied pressure, and the observed pressure should be corrected before the shear stress τ is calculated. This correction can be represented by the following equation known as the Hagenbach correction (11):

$$\Delta P' = \Delta P - m\rho Q^2/\pi^2 R^4 \quad (41)$$

where $\Delta P'$ is corrected pressure, ΔP is observed pressure, and m is the kinetic energy correction factor. Values of m found experimentally range from zero to 1.55. This variation in correction factor should not be considered poor since in most instances m depends greatly on the individual system and its design and operation. Also the magnitude of the correction is usually much smaller than the discrepancies among replicate observations and is only important for very high fluid velocities.

In all capillary viscometers, a liquid in a wide reservoir enters the capillary tube in a converging stream and comes out either into open air or another wide reservoir in a divergent stream. Differences in velocity between adjacent lines of flow in these streams require using energy to overcome viscous forces. The internal frictional losses due to both sudden contraction and expansion are functions of the ratio of area of the reservoir to capillary cross-sectional area, the kinetic energy of the fluid, the nature of the test fluid, and the shapes of capillary ends. Trumpet-shaped or rounded entrances and exits give less frictional loss than square ends. Couette (5) was the first to suggest

a correction for end effects, and it usually takes the form

$$L' = L + \Delta L = L + NR \quad (42)$$

where L' is an equivalent length, L is the measured length, and N is the Couette coefficient. The value of N is often quite small and by using relatively large values of L/R in the capillary tubes this correction becomes insignificant. Most authors agree that a ratio of $L/R \geq 200$ is sufficient. In this study, L/R ratios ranged from approximately 300 to 2,000.

An isothermal condition is usually assumed in the derivation of the equations describing fluid flow since the temperature coefficient of viscosity of liquids may be large. An accurately controlled thermostat is an essential part of any well-designed capillary viscometer, and the temperature at which the viscosity is measured must always be clearly stated. The problems associated with obtaining an isothermal condition are not always recognized by some investigators, thus making their results questionable. Substantial radial and axial temperature gradients can be present if the thermostat is not properly designed.

Another heat effect is the rise of temperature resulting from dissipation of mechanical energy along the length of the capillary tube. The part of the pressure which has to overcome the force of friction is dissipated as heat according to the equation given by Ram and Tamir (19)

$$M = \mu_a (-dv/dr)^2 \quad (43)$$

where M has units of energy per unit time per unit volume. Obviously M increases as shear rate increases, and this may affect the flow

readings at extreme values of shear rate. The maximum temperature rise can be estimated from the following equations:

$$\rho C_p (dT/dt) = \mu_a (-dv/dr)^2 \quad (44)$$

$$\rho Q C_p \Delta T = \mu_a (-dv/dr)^2 V \quad (45)$$

where V is the volume of the capillary. A mean value of shear rate such as $(-dv/dr)_w/2$ can be used for estimation. Substituting this mean shear rate into Equation 45 and rearranging

$$\Delta T_{\max} = \frac{\mu_a (-dv/dr)_w^2 \pi R^2 L}{4\rho Q C_p} \quad (46)$$

A good check for the significance of the dissipation value is provided by a Newtonian straight line for the calibration oil in the high shear rate range.

In capillary viscometers involving externally applied pressure, the effective pressure drop across the capillary is the sum of the externally applied pressure and that due to the head of liquid in the viscometer reservoir and the capillary tube; the head term of course decreases during the data-taking, and correction must be made for this decrease. An arithmetic mean head correction is used in this study, although some authors recommend using a logarithmic head correction.

Errors can be introduced by using the nominal diameters of the capillary tubes obtained from the manufacturer, since even fine-bore tubing has significant variance over a reasonable length. The safest method is to obtain the effective hydraulic diameters from calibration runs with Newtonian fluids of known viscosity using the Poiseuille

equation.

Absolute cleanliness of capillary viscometers is essential for accurate and reproducible results. This is probably one of the worst disadvantages to capillary viscometers. Cleaning procedure depends on the fluid being tested. When the fluids are standard hydrocarbon oils, treatment with a fairly volatile solvent is recommended followed by purging with dry air or nitrogen. When the fluids are polymers dissolved in water such as CMC solutions, treatment with large amounts of hot water followed by an acetone rinse and dry air or nitrogen purge is sufficient. Care should be taken to clean the capillary tubes as soon as possible after using them. CMC solutions tend to form a hard film upon evaporation which would affect the effective diameter of the capillary tube and give erroneous results.

Calibration

The Hagen and Poiseuille relationships offer a relatively simple approach to calibration and are adequate for the high L/R ratios being used. Employing a Newtonian fluid of known viscosity, one can calibrate the effective hydraulic diameter and a combined coefficient to account for kinetic energy and end effects. The total applied pressure is composed of the gas pressure plus head pressure, and the resisting forces are the pressure drop due to flow in the test section (ΔP_1) and the pressure drop due to kinetic energy and entrance and exit effects (ΔP_2). Thus

$$\Delta P_1 + \Delta P_2 = P_{\text{gas}} + P_{\text{head}} \quad (47)$$

For a Newtonian fluid from Poiseuille's equation,

$$\Delta P_1 = K_1 Q$$

or

$$K_1 = \Delta P_1 / Q = 8\mu L / \pi R^4 g_c \quad (48)$$

From Hagen's equation (10)

$$\Delta P' = K_1 Q + K_2 Q^2$$

or

$$\Delta P' / Q = K_1 + K_2 Q \quad (49)$$

where $\Delta P'$ is head-corrected pressure drop. Thus by measuring a set of values for $\Delta P'$ and Q for a Newtonian fluid of known viscosity and plotting these values as $\Delta P' / Q$ versus Q , a straight line of intercept K_1 and slope K_2 should result. Substituting the value of K_1 in Equation 48, the effective hydraulic radius is determined; and K_2 becomes the correction constant for that particular tube in that particular reservoir.

CHAPTER IV

EXPERIMENTAL APPARATUS

Very few commercial instruments are available which possess all of the required characteristics for a capillary viscometer at a reasonably modest cost. Since the construction of capillary tube viscometers is relatively simple, it is common to build these instruments in a laboratory workshop as done in this study. A complete capillary viscometer consists of five essential parts: (1) a fluid reservoir, (2) interchangeable capillary tubes of known dimensions, (3) a unit for controlling and measuring the applied pressure, (4) a unit for determining flow rate, and (5) a unit for controlling temperature. A picture and schematic diagram of the complete system are shown as Figures 4 and 5, respectively.

Test Fluid Reservoir

The fluid reservoir was designed to accommodate a 1,000 psig maximum working pressure with no pressure leakage. A detailed drawing is shown as Figure 6. Type 304 stainless steel extra heavy Schedule 80 seamless pipe was used for the wall of the reservoir. The inside surface of this pipe was honed to a smooth finish to minimize holdup of the test fluid. The pipe is approximately 14 1/2 inches long and 3.82 inches internal diameter. Its maximum capacity is about 2,700 cc. A groove was machined at each end of the pipe to accommodate a 4-inch

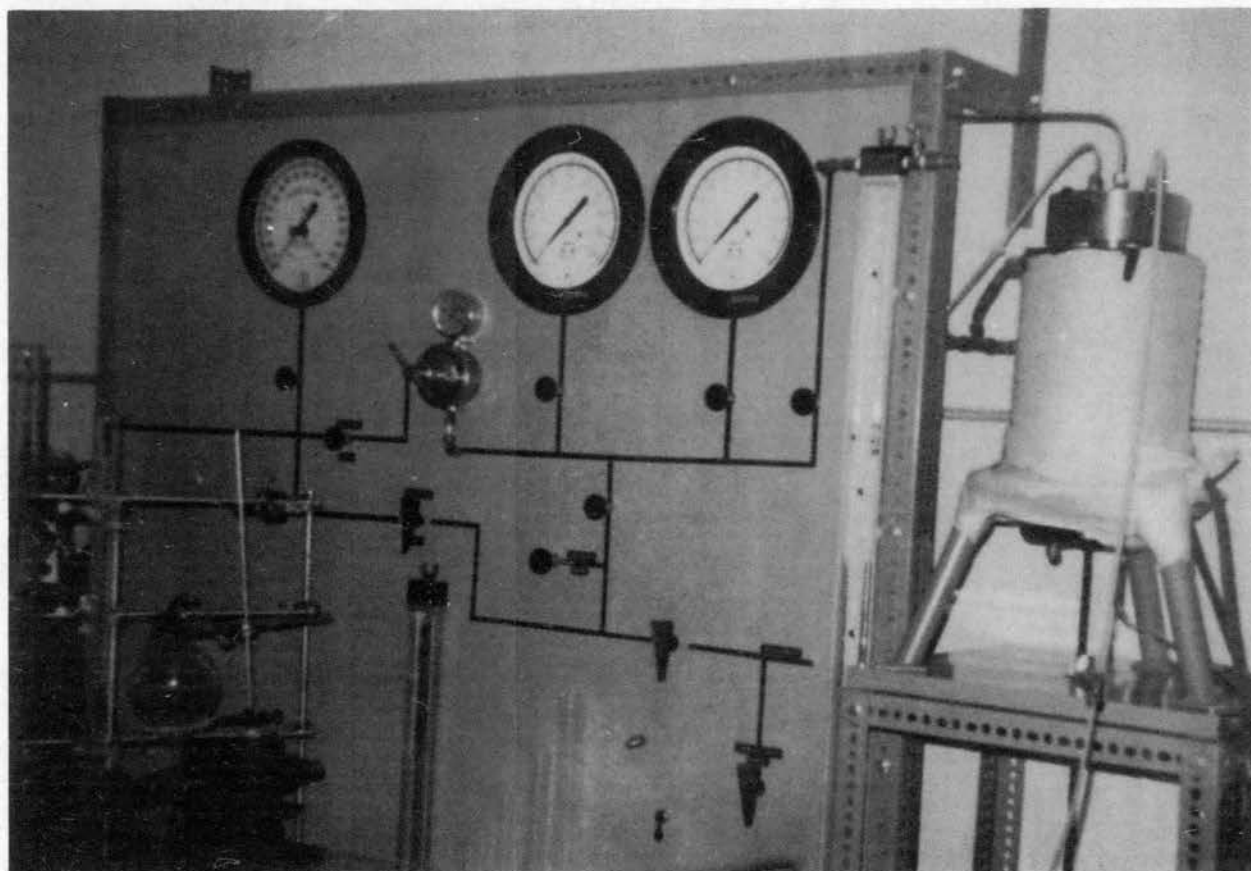


Figure 4. Photograph of Viscometer System

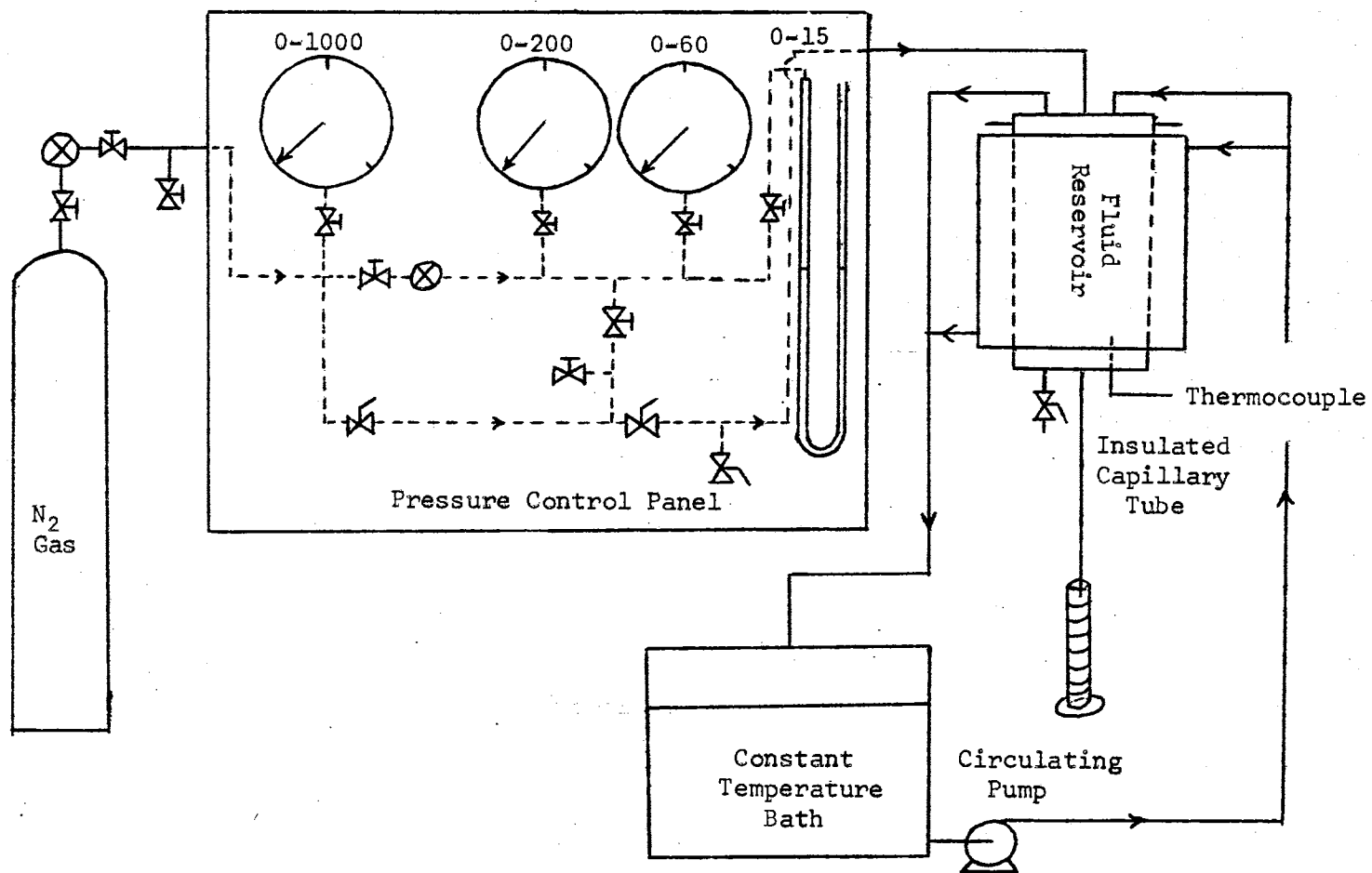


Figure 5. Schematic Diagram of Capillary Viscometer System

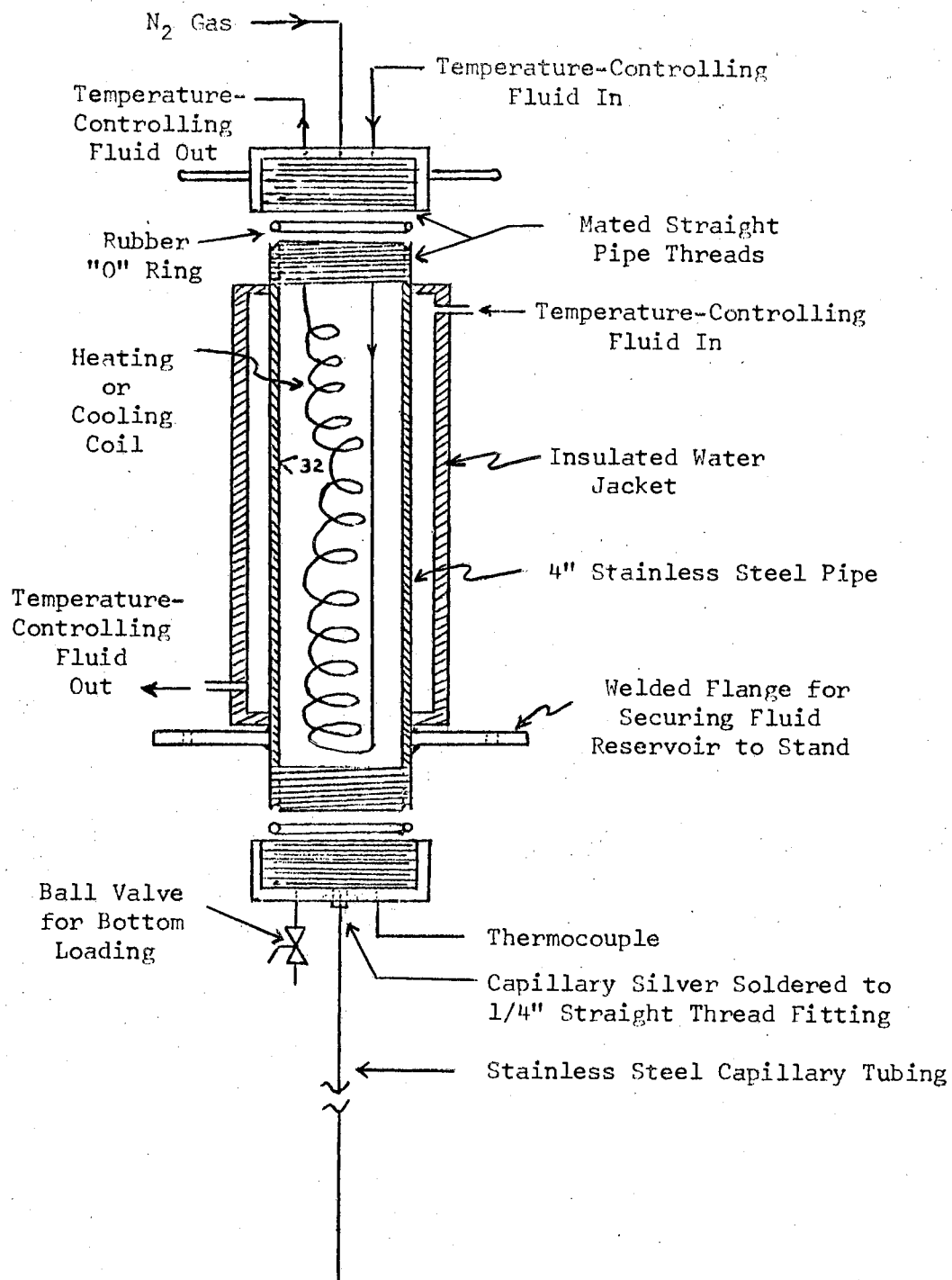


Figure 6. Schematic Drawing of Fluid Reservoir

rubber "O"-ring, and approximately one inch of straight threads were cut below the "O"-ring groove on the outside surface of the pipe.

Type 304 stainless steel forgings were machined for the top and bottom caps of the reservoir with mating internal threads cut on each to enable closure. The actual pressure seal is made by the "O"-ring, and the threads do not have to be tightened more than hand-tight to give proper orientation of cap to "O"-ring. Three fitting holes were tapped in each cap. On the top cap, one 1/4-inch NPT hole in the center is used to bring the pressurized dry nitrogen from the pressure control panel. The other two 1/4-inch NPT holes on the top cap are threaded from both the inside and outside faces so that internal temperature coils can be plumbed into and out of the reservoir. Two handles were placed at 180 degrees apart to enable easy opening and closing. On the bottom cap, two 1/4-inch NPT holes were tapped: one for placement of a sheathed thermocouple near the capillary tube entrance, the other for bottom pressure loading of test fluid. With some very viscous fluids, bottom loading is recommended to minimize the chance of entrapping gas pockets in the fluid. The other ways for loading samples are either through the top center pressure fitting or by unscrewing the top cap and pouring the fluid down the side of the reservoir. The center hole on the bottom cap was counterbored and tapped with 1/4-inch straight thread to accommodate a special Swagelok fitting used on each capillary tube. The reason for counterboring was in order to have the top of each capillary fitting exactly flush with the inside face of the bottom cap. The reservoir was hydrostatically pressure tested to 1,500 psi after machining was completed to ensure safety and also to check for leakage. No leakage or pressure drop was observable after leaving it

stand overnight.

Capillary Tubes

Nominal tube inside diameters of $1/32$, $1/16$, $1/8$, and $5/32$ inches and lengths in each diameter of 18, 24, and 30 inches were chosen for flexibility in attaining shear rates and also so that the calibration could be compared among a number of tubes. Also by using different diameters and lengths, thixotropic and rheopectic fluids can be qualitatively identified. This method has been shown experimentally by Ambrose and Loomis (1) and is illustrated by the curves of Figure 7. For quantitatively characterizing these fluids, this method is unsatisfactory, and a rotational viscometer, where uniform rates of shear are possible, is recommended. Each capillary tube was inserted into a separate Swagelok special tube fitting and silver soldered in place. Each tube was then rounded into a trumpet shape at the entrance. A $1/2$ -inch diameter "O"-ring is a part of each fitting and fits snugly against the counterbored hole when the tube is in its proper position. A special split-socket wrench was made to fit around the tube and screw the fitting into the counterbore. A drawing of a typical tube is shown as Figure 8. The length of each tube was measured with a cathetometer and are listed in Table I along with calibrated diameters and correction coefficients. The minimum L/R ratio is approximately 306.

Pressure Control and Measurement

A diagram of the pressure control panel is Figure 9. Pressure is supplied by a standard cylinder of compressed dry nitrogen gas attached to the panel. An attached high pressure regulator lowers pressure from

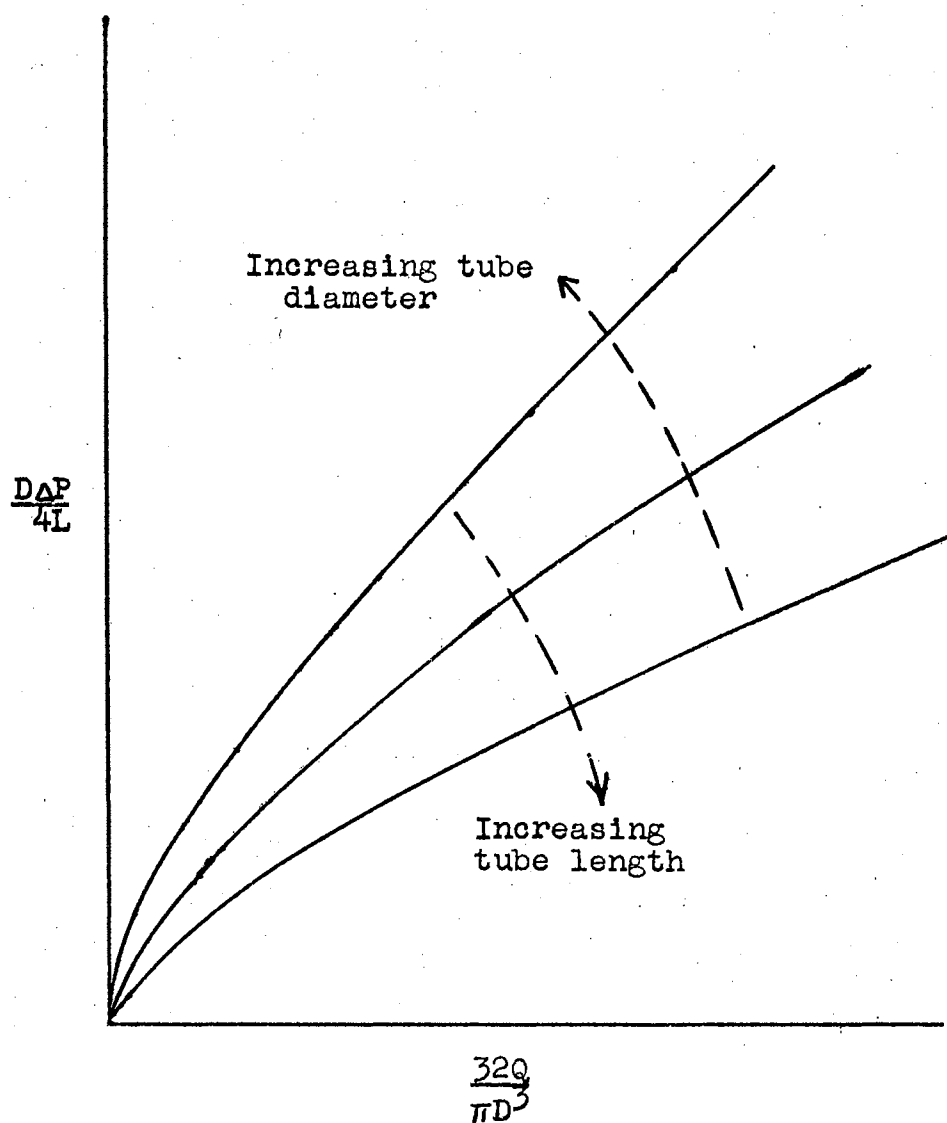


Figure 7. Tube Flow of a Thixotropic Fluid

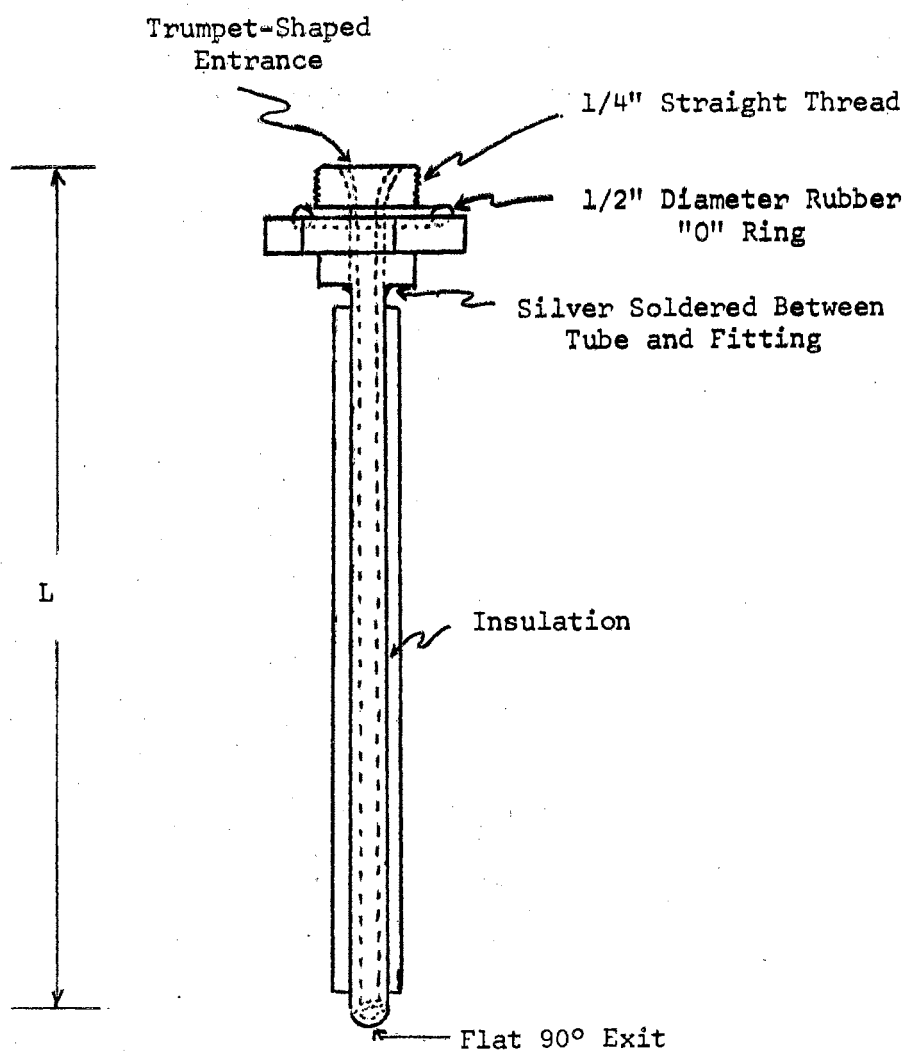


Figure 8. Drawing of Typical Capillary Tube

TABLE I
CAPILLARY TUBE CONSTANTS

<u>DESIGNATED TUBE NUMBER</u>	<u>NOMINAL LENGTH (ft.)</u>	<u>NOMINAL DIAMETER (in.)</u>	<u>MEASURED LENGTH (ft.)</u>	<u>CALIBRATED HYDRAULIC DIAMETER (in.)</u>	<u>L/R RATIO</u>	<u>CALIBRATED TUBE CORRECTION CONSTANT ($\text{lb}_f\text{-sec}^2/\text{ft}^8$)</u>
1	1.5	0.0313	1.510	0.02998	1210	1.674×10^{11}
2	2.0	0.0313	1.997	0.02994	1600	1.745×10^{11}
3	2.5	0.0313	2.503	0.02995	2006	1.745×10^{11}
4	1.5	0.0625	1.501	0.06096	590	5.130×10^9
5	2.0	0.0625	2.001	0.06276	766	7.050×10^9
6	2.5	0.0625	2.493	0.06228	962	5.005×10^9
7	1.5	0.1250	1.505	0.11820	306	7.811×10^8
8	2.0	0.1250	1.993	0.11796	404	8.603×10^8
9	2.5	0.1250	2.505	0.11783	510	8.817×10^8
10	2.0	0.1560	1.998	0.1483	324	2.52×10^8
11	2.5	0.1560	2.501	0.1495	402	3.93×10^8

KEY

- | | | |
|--|---|---------------------------|
| 1. 1,000 psi Gauge Safety Valve | } | Gauge
Safety
Valves |
| 2. 200 psi Gauge Safety Valve | | |
| 3. 60 psi Gauge Safety Valve | | |
| 4. Manometer Safety Valve | | |
| 5. Low Pressure System
Safety Valve | | |
| 6. Low Pressure System
Safety Valve | | |
| 7. Low Pressure Bleed Valve | | |
| 8. High Pressure System
Safety Valve | | |
| 9. High Pressure System
Safety Valve | | |
| 10. High Pressure Bleed Valve | | |
| 11. Control Valve to Viscometer
Reservoir | | |
| 12. Back Pressure Exhaust Valve | | |
| 13. Low Pressure Regulator | | |
| 14. High Pressure Regulator | | |

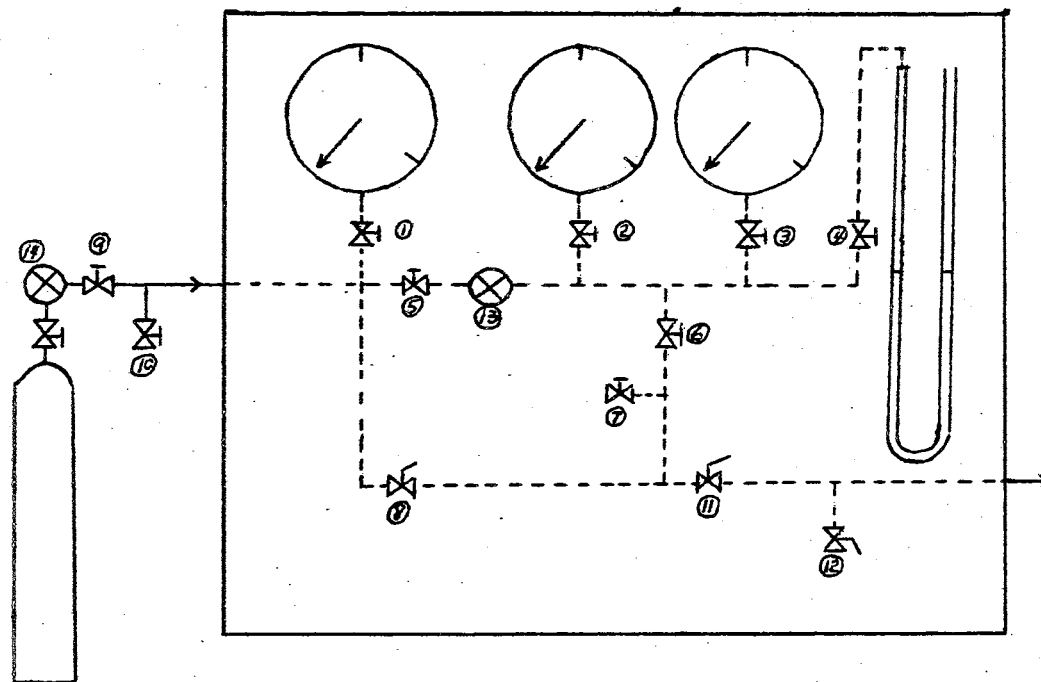


Figure 9. Diagram of Pressure Control Panel

cylinder pressure of 2,200 psig to 1,000 psig or less. Three 8 1/2-inch diameter dial gauges and a 36-inch mercury manometer are used for pressure readout in suitable ranges. The 0-1,000 psi gauge is a Kahn and Company Helicoid test gauge with 5 psi subdivisions. The two lower-range gauges are Marsh test gauges with "read-easy" mirror dials and accurate to within $\pm 1/4$ of 1 percent of the maximum dial reading. The 0-200 psi gauge has 1 psi subdivisions, and the 0-60 psi gauge has 0.2 psi subdivisions. All three pressure gauges were calibrated with a Budenberg dead-weight tester. These gauges should be recalibrated periodically to maintain the accuracy of the system. The high pressure line of the control panel is 304 stainless steel tubing and is plumbed directly from the nitrogen cylinder regulator to the 1,000 psi gauge. For low pressure work, a 0-400 psi Matheson regulator is used to direct flow to the low pressure gauges and manometer. Care should always be taken to check that all other gauges are closed off from pressure except the particular one being used so that gauge movements will not be damaged by overpressure. Any pressure may be set on the panel by proper manipulation of the regulator and the bleed valve. Once the approximate pressure selected is set, the ball valve connecting the panel to the viscometer reservoir is opened and flow commences. Once flow is completed for a particular run and pressure is cut off from the viscometer, back pressure in the reservoir can be quickly released by the exhaust ball valve. This prevents using excessive amounts of test fluid.

Volumetric Flow Measurement

Once steady-state flow is obtained and steady pressure is reached on the gauge, the time between two levels on a conveniently-sized

graduated cylinder is determined by stopwatch measurement. An alternate system has been built but not used in this study. It consists of a leak-tight gas displacement system attached to a closed receiving vessel such as a 2,500 cc filter flask with a side-arm modified to fit a Swagelok compression fitting. As test fluid flows into the flask, gas is displaced and it displaces liquid from a reservoir to a suitable size burette depending on flow rate. Gas compression or expansion is eliminated by maintaining both receivers at atmospheric pressure, as noted by a 15-inch manometer, through a leveling device consisting of screw-jacks. This alternate system would be especially suited to working with high flow rates where gas entrainment is a problem. It is also recommended in the case of a volatile or hazardous test fluid.

Temperature Control

The viscometer reservoir is temperature-controlled externally by a mild steel insulated jacket welded to it and internally by a 1/4-inch copper tubing coil as shown in Figure 6. Fluid is continually circulated through the jacket and coils by a Blue M Electric constant temperature bath. The bath is equipped with a refrigeration unit as well as heating coils. Its temperature range is from -25 to 100 degrees Centigrade, and it has a hand-dial assembly for selecting and calibrating at a particular temperature.

A sheathed copper-constantan thermocouple is attached to the bottom cap of the viscometer reservoir with the tip close to the entrance of the capillary tube. The thermocouple is connected to a portable Leeds and Northrup potentiometer. Thermocouple calibration tables accompanying the potentiometer were used to calibrate the thermocouple.

Each capillary tube is insulated by asbestos cloth wrapped its entire length and covered by plastic tape; however, the tubes are not temperature-controlled by the bath.

CHAPTER V

EXPERIMENTAL PROCEDURE

The constant temperature bath is usually turned on at least two hours in advance of the time runs are to be made if the temperature selected for the runs is not close to ambient temperature. This allows sufficient time for the viscometer reservoir to reach a steady temperature. The bath should be set about 2°F above selected temperature for above-ambient temperatures and about 2°F below selected temperature for below-ambient temperatures. This is necessary due to heat losses in the circulation lines to the viscometer from the bath.

The sample to be run is preheated or precooled in the constant temperature bath at the same time the reservoir is attaining steady temperature. Depending on the consistency of the sample and the diameter of the capillary tube to be used, a small piece of flexible rubber tubing with a pinch clamp connected is placed over the open end of the tube to prevent drainage of sample under its own head before runs are to be made.

The preheated sample is quickly poured into the viscometer reservoir either by unscrewing the top cap or through the pressure tap in the top cap. The initial volume of the sample should be determined beforehand either directly or from reservoir calibration. The viscometer reservoir is calibrated so that the distance from the sample level to the top of the reservoir is measured, and the corresponding

volume is read from a graph. For a completely unknown sample, it is wise to fill the entire volume of the reservoir so that many different pressures can be used and thus a wide range of shear rates can be obtained. Once the sample is in the reservoir and the initial volume is known, the top screw cap is secured and the pressure line from the control panel is tightened on the center fitting in the top cap.

The pressure to the control panel is turned on by the valve on the compressed gas cylinder (dry nitrogen) and turning the high pressure regulator handle clockwise until the desired pressure ($< 1,000$ psi) registers on the small left-hand dial gauge. Care should be taken to insure that initially the low and high pressure safety valves are closed and also that the gauge and manometer safety valves are also closed. The regulator and $1,000$ psi gauge safety valves are then opened and pressure is registered on the $1,000$ psi gauge. The high pressure safety valve is opened at this time. Again, it should be noted that the safety bleed, low pressure safety, and control valves are closed.

If a complete range of shear rates is needed, it is best to start with the highest working pressures while the viscometer reservoir is relatively full and work down to lower pressures as the volume decreases. This not only is a safety feature if the sample tends to core, but it also conserves the amount of nitrogen gas used. A pressure is selected on the $1,000$ psi gauge between 200 and $1,000$ psi by manipulation of the high pressure regulator and the high pressure bleed valve. Once pressure is set, a proper size graduated cylinder is selected and placed under the capillary tube; and the flexible rubber tubing and pinch clamp are removed from the tube. Temperature of the sample near the tube entrance is recorded from the potentiometer reading for the

copper-constantan thermocouple.

The system is now ready for pressure to be admitted to the viscometer reservoir. This is done by opening the control valve to the reservoir, which is a quarter-turn ball valve. There will be a momentary transient period while pressure and flow build up to steady-state conditions. When pressure is steady, time measurement is started on a precision stopwatch at some convenient volume graduation on the graduated cylinder. After a reasonable volume of sample has flowed, a second convenient volume graduation is chosen and time measurement is stopped. Immediately, the control valve to the reservoir should be closed and the back pressure exhaust valve opened. This reduces flow to a minimum and conserves sample. The steady-state reading of pressure, cylinder graduations, and time of flow are recorded. A running account of the volume in the reservoir is obtained by recording the total volume of sample used for each run and subtracting this from the initial volume or the volume remaining from the previous run.

To get another point on the flow curve, the pressure is reset on the 1,000 psi gauge by manipulation of high pressure regulator and bleed valve; and the entire procedure is repeated with the appropriate graduated cylinder selected for the flow to be encountered. This can be judged from a little experience with the system. It is possible to set too high a pressure and the cylinder will be practically filled before steady-state is achieved. If this happens, quickly close the control valve and open the back pressure exhaust valve; then select a lower operating pressure.

When the high pressure runs are finished, the high pressure safety valve is closed; and gas in the high pressure line between the safety

valve and control valve is released by the safety bleed valve. Pressure is set on the 1,000 psi gauge in the range of 300-400 psi, and the low pressure safety valves are opened. Care should be taken to insure that the low pressure regulator is not open initially to prevent possible damage to gauges. The 200 psi gauge safety valve is opened and the low pressure regulator is turned clockwise until pressure registers on the gauge. Pressure is set by manipulation of low pressure regulator and safety bleed valve. The control valve to the reservoir is opened and flow measurement is made as mentioned previously. The procedure is repeated for the 60 psi gauge and the 36-inch mercury manometer to obtain lower pressure measurements.

If it is desired to use different capillary tubes during the flow runs, they can be changed in several ways. One way is to unscrew the tube and quickly plug the hole until a new capillary is put in place. This is an awkward and sometimes messy procedure. Another way is to partially remove the tube and remove the top cap of the reservoir. A fabricated T-rod with an identical threaded fitting as is on the tubes is screwed into the bottom cap from above. Tubes are then interchanged, the T-rod removed, the tube tightened, and the top cap replaced. If a more convenient method is wanted, a ball valve should be placed between the bottom cap and the capillary tube. The system must then be recalibrated due to the valve.

Once the flow runs are completed, the reservoir and capillary tubes are cleaned thoroughly unless material of the same type is to be run in the near future.

CHAPTER VI

PRESENTATION AND DISCUSSION OF RESULTS

Calibration Results

Initial calibration runs were made with Phillips Petroleum KC 10 oil. This oil has the known viscosity versus temperature curve shown in Figure 10. Since kinematic viscosities are given, it was necessary to determine the density of the oil as a function of temperature as shown in Figure 11. Capillary tubes used in this study are designated by number as shown in Table I. This table also gives measured length, nominal diameter, nominal length to diameter ratio, and calibrated constants for each tube.

The smaller diameter tubes were run with KC 10 oil at 100°F and the flow results are shown in Figures 12 and 13. The resultant negative slopes indicate slight deviation from Newtonian behavior. Thus, the oil cannot be used to calibrate the tubes by this method. Experimental and calculated data used in making plots for all runs are listed in Appendix B. The computer program list used in making calculations for both calibration and CMC runs is given in Appendix C.

Distilled water at ambient temperature (72.2°F) running under its own head gave much better results than the KC 10 oil as shown by the typical curves in Figure 14. Using the data for distilled water from tubes 1 through 6, their diameters and correction coefficients were

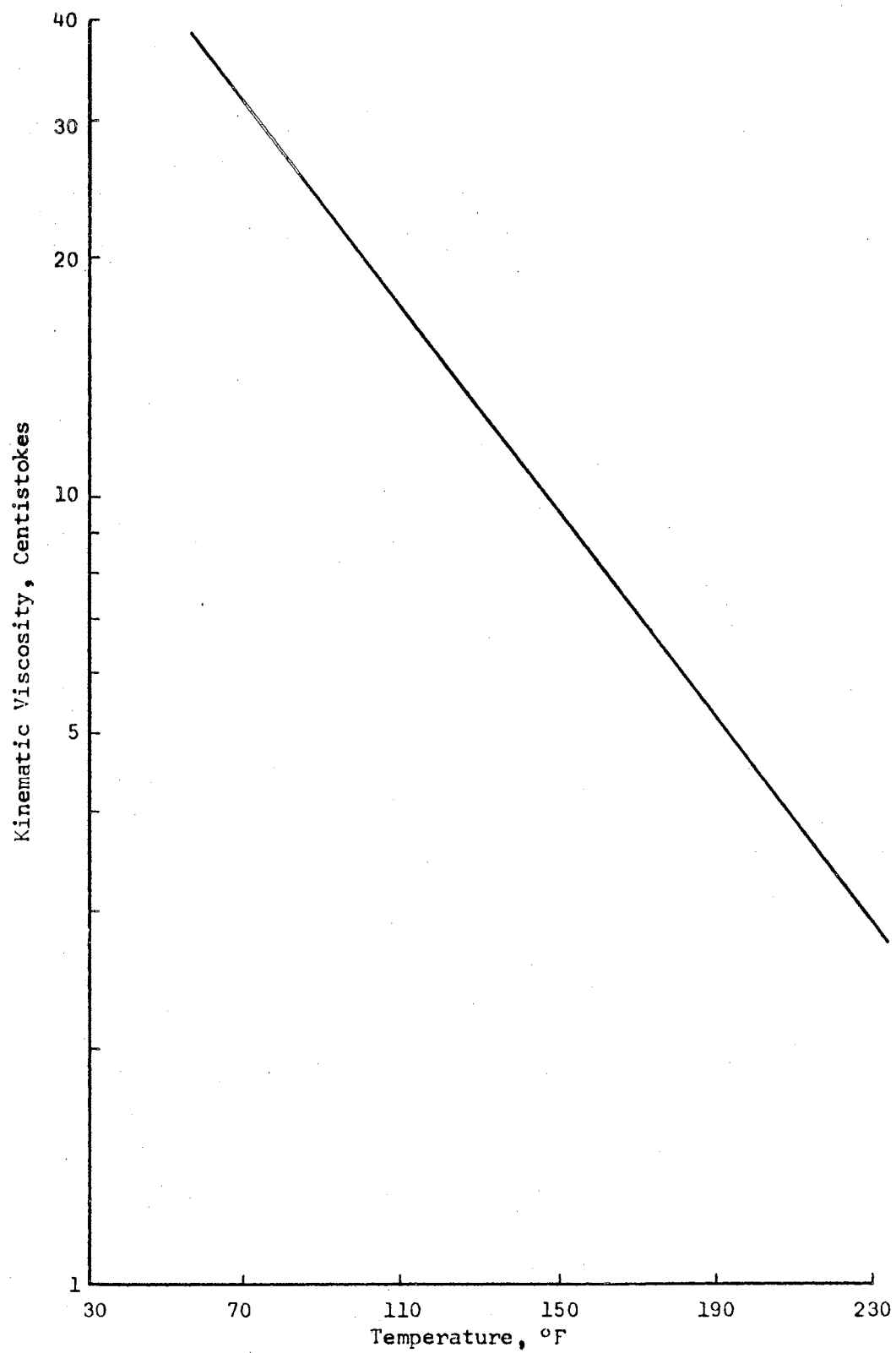


Figure 10. KC 10 Oil Viscosity Versus Temperature

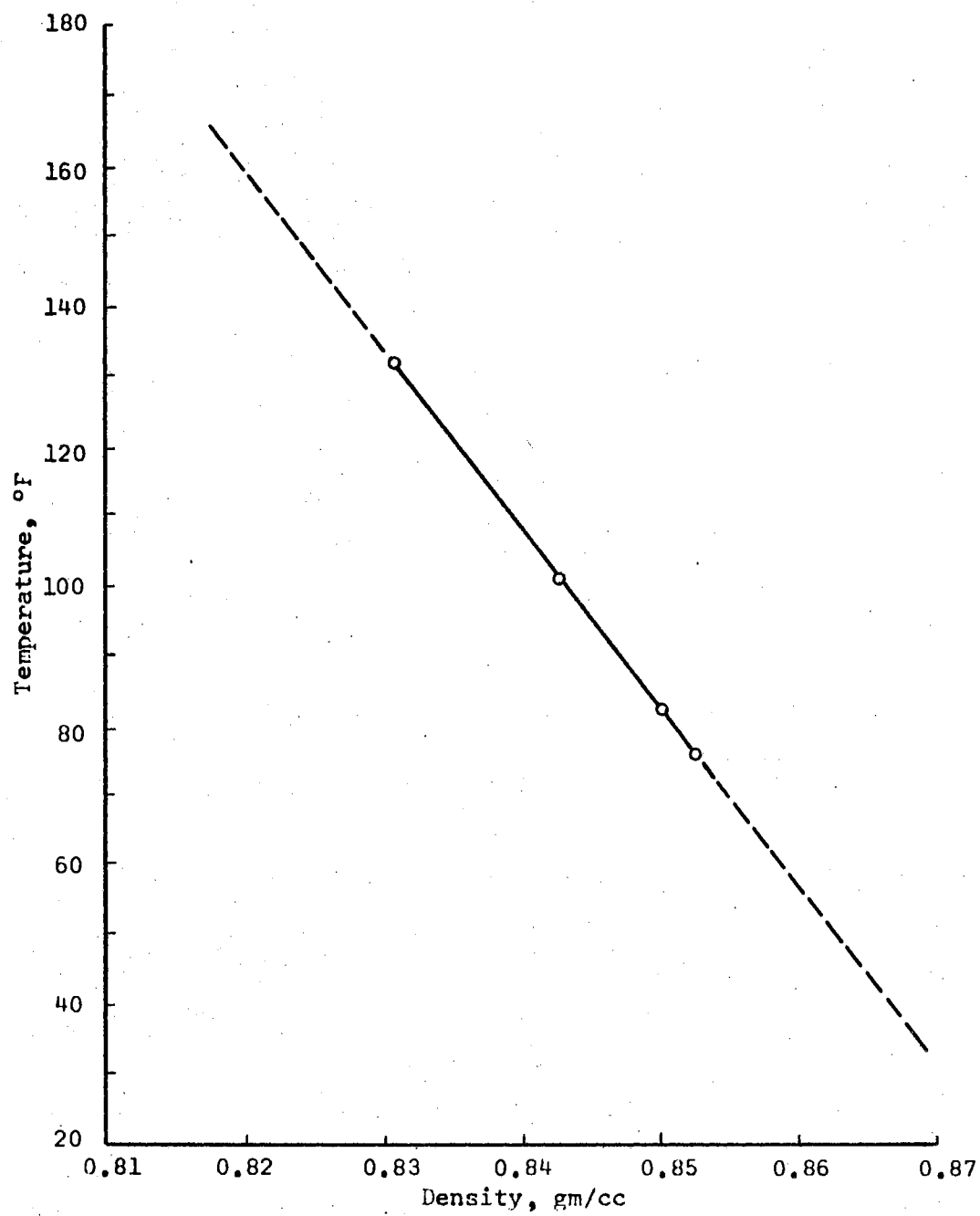


Figure 11. KC 10 Oil Density Versus Temperature

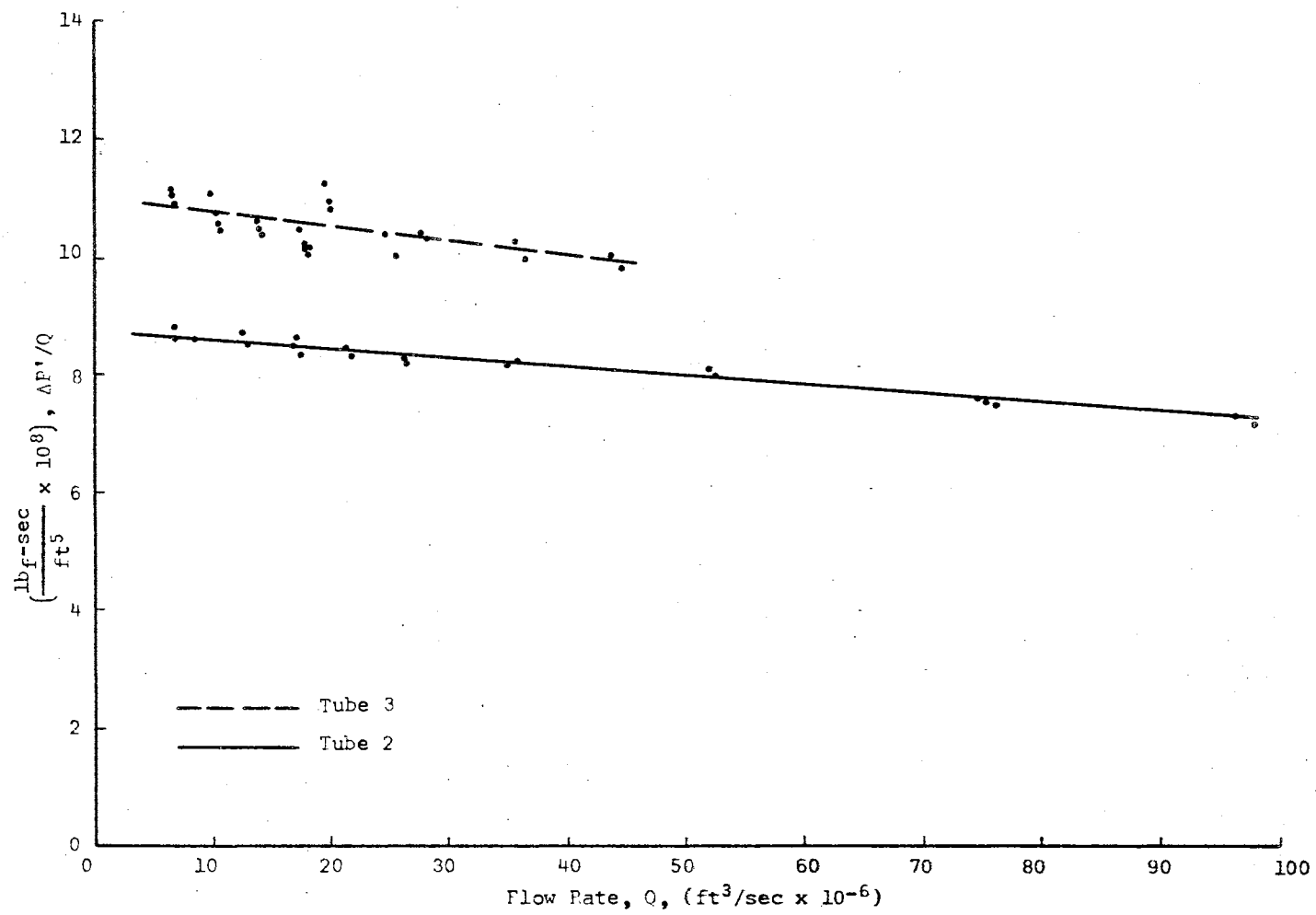


Figure 12. Flow Calibration Results for KC 10 Oil at 100°F

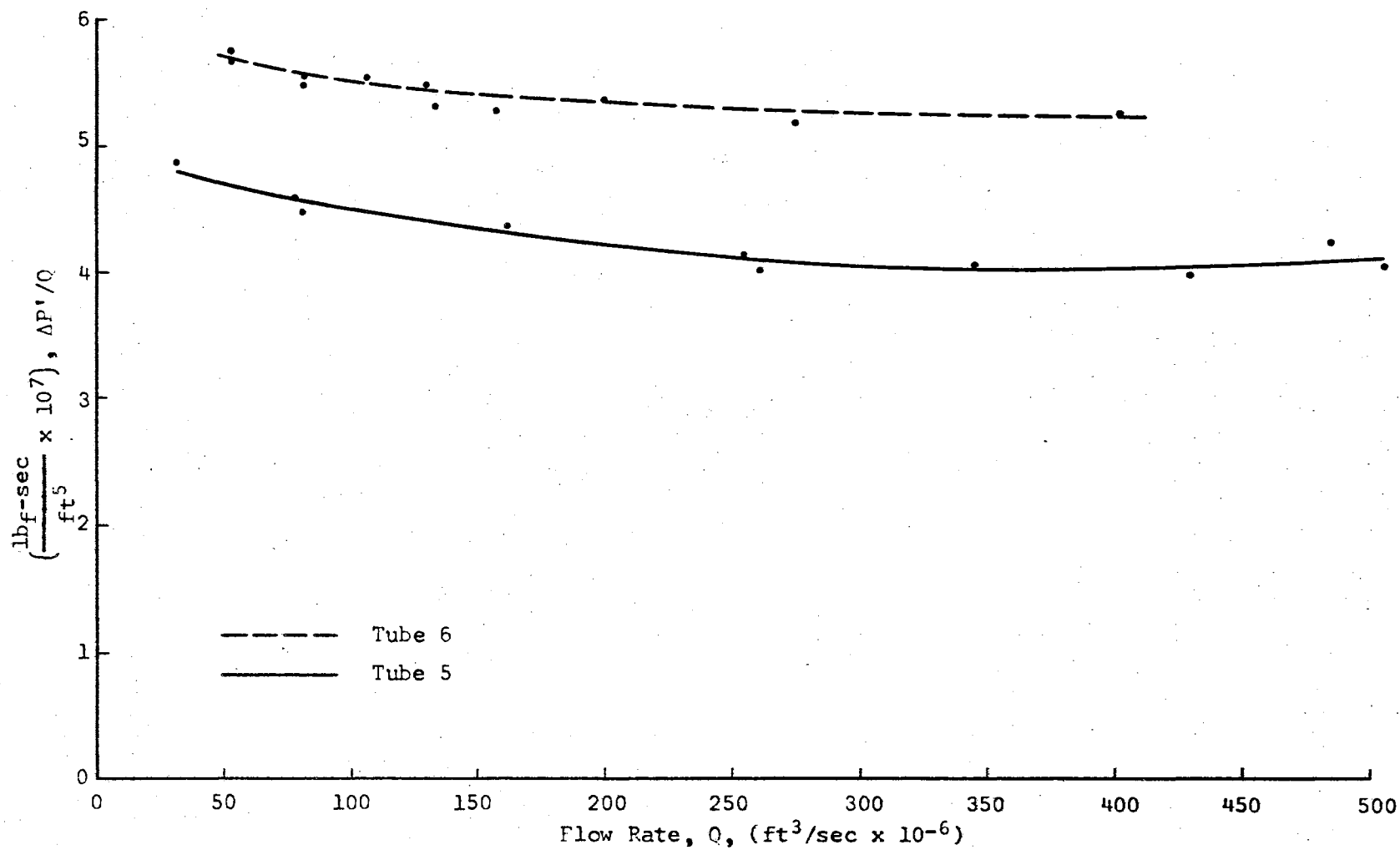


Figure 13. Flow Calibration Results for KC 10 Oil at 100°F

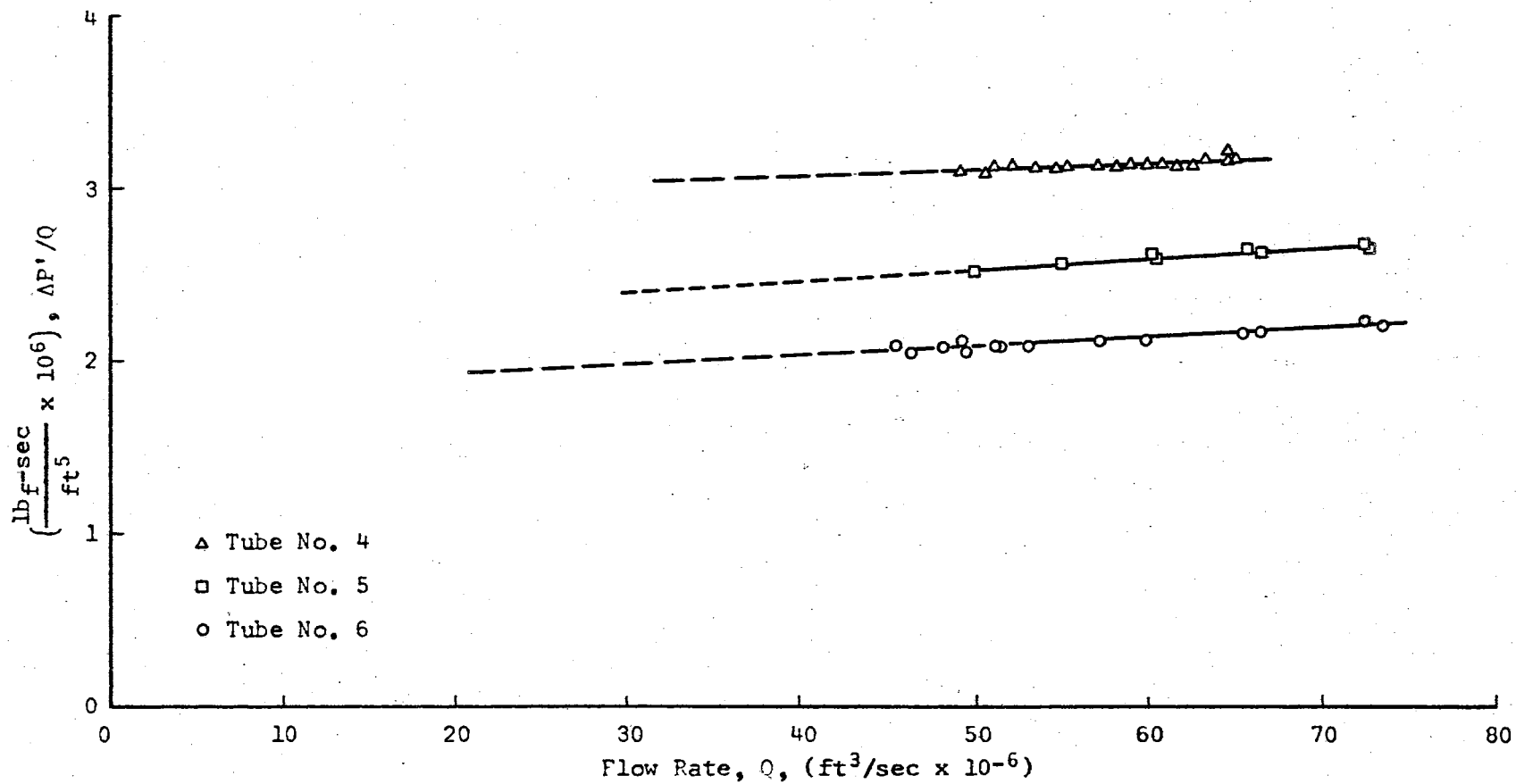


Figure 14. Flow Calibration Results for Distilled Water at 72°F

calculated. Tubes 7 through 11 could not be calibrated in this manner since water flow becomes turbulent even under its own head pressure in these tubes. Since flow rate ranges overlap considerably among the tubes, the larger tube diameters and coefficients were determined from KC 10 oil data using the calibrated tube data as a basis. As a check on the constants, data for tubes were plotted as shear stress versus shear rate for both distilled water and KC 10 oil. All data for a particular fluid should fall on one curve if the fluid is not time dependent. As shown by Figures 15 and 16, the data are consistent. NBS oil M was also run and gave agreement with known viscosity as shown in Figure 17.

CMC Solution Results

Hercules Type 7H Sodium Carboxymethylcellulose (CMC) solutions of approximately 1 and 1 1/2 percent by weight CMC in tap water were prepared by Mr. Don Adams and Mr. Kohei Ishihara. Most of these samples had been subjected to relatively high temperatures (140-160°F) and continuous shearing forces from pumping in a pipe loop. This pumping was in connection with research on heat transfer in a tube bank. Thus, it was possible to obtain samples at various times during this pumping procedure and examine how the material was changing by use of the calibrated capillary viscometer.

An initial sample of 1 percent CMC at 75°F was run. A characteristic flow diagram is shown for this material as Figure 18. As seen in the figure, the material closely approximates a power law fluid over short ranges of $32Q/\pi D^3$, but the plot is curved and not a straight line over the complete range. The curve is fitted well by a second degree

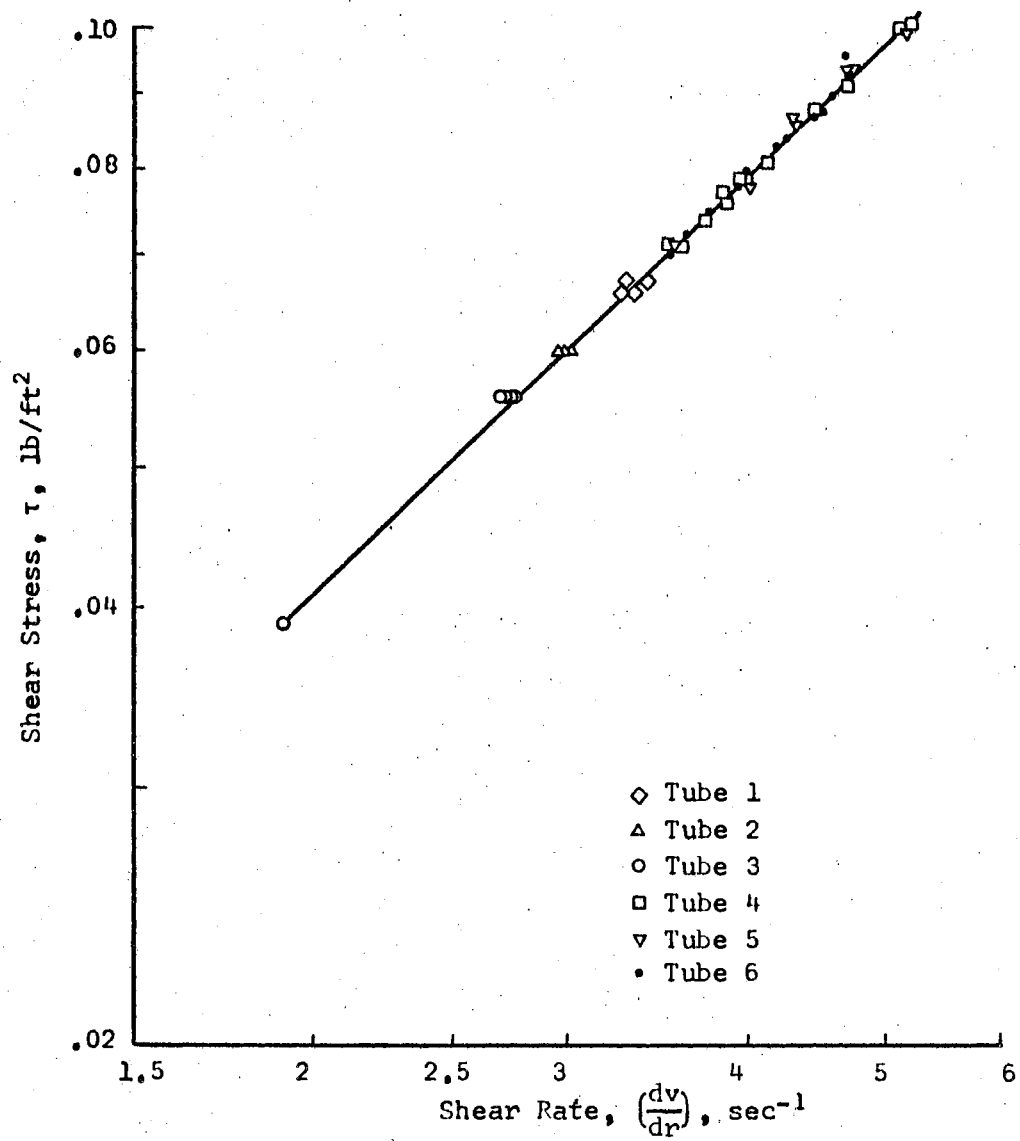


Figure 15. Shear Stress-Shear Rate Diagram for Distilled Water at 72°F

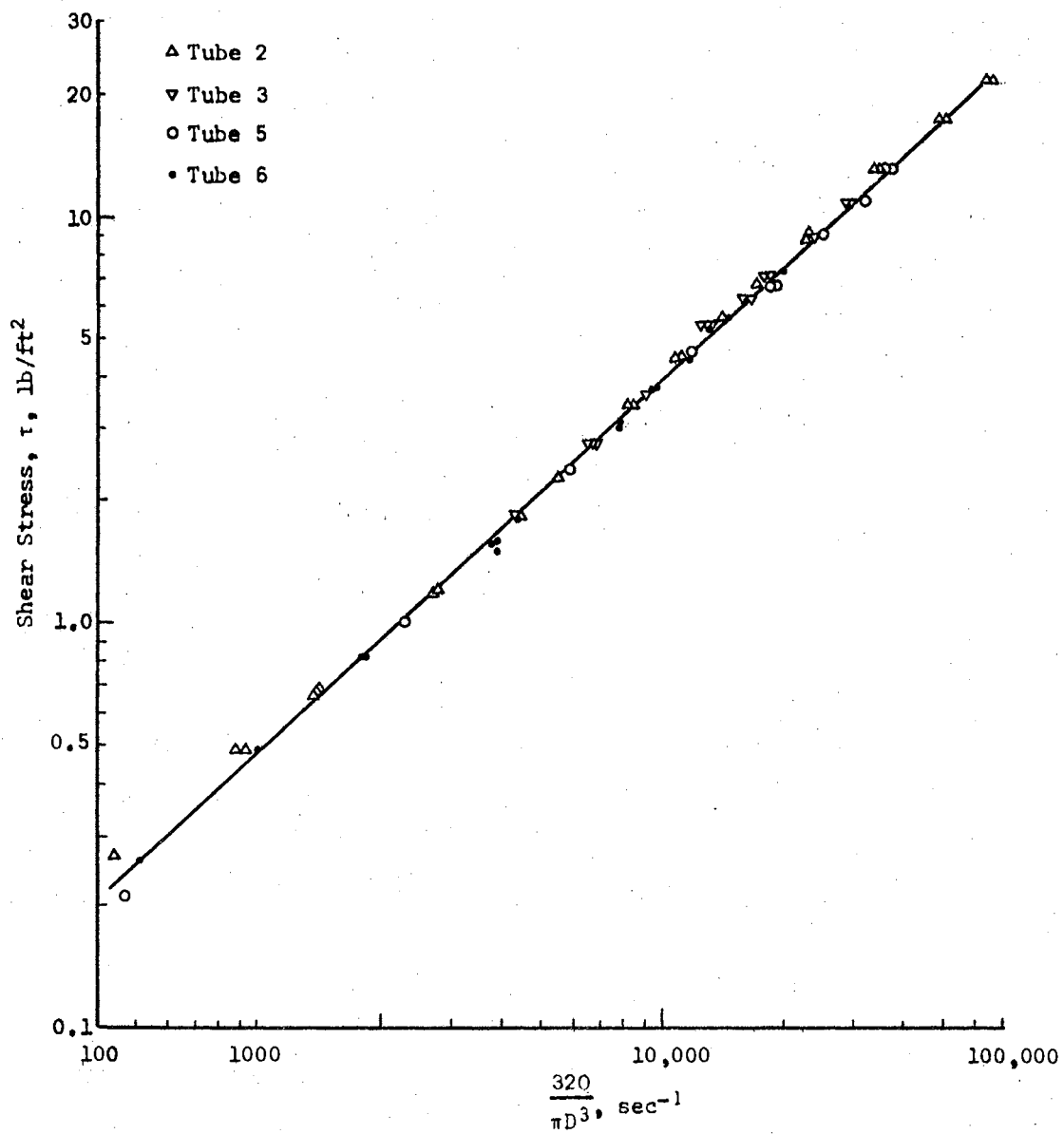


Figure 16. Flow Curve for KC 10 Oil at 100°F

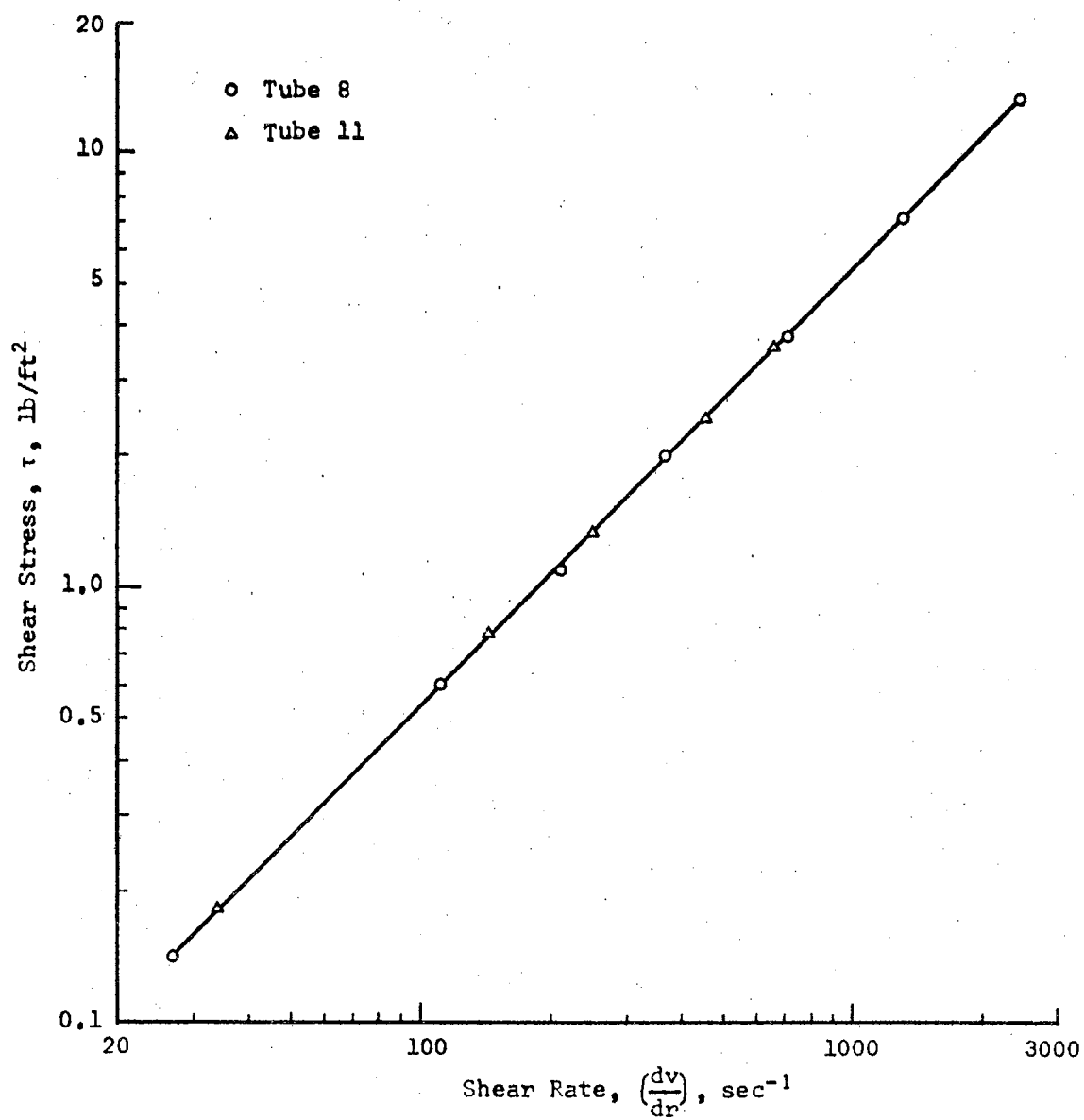


Figure 17. Shear Stress-Shear Rate Diagram for NBS Oil M at 74°F

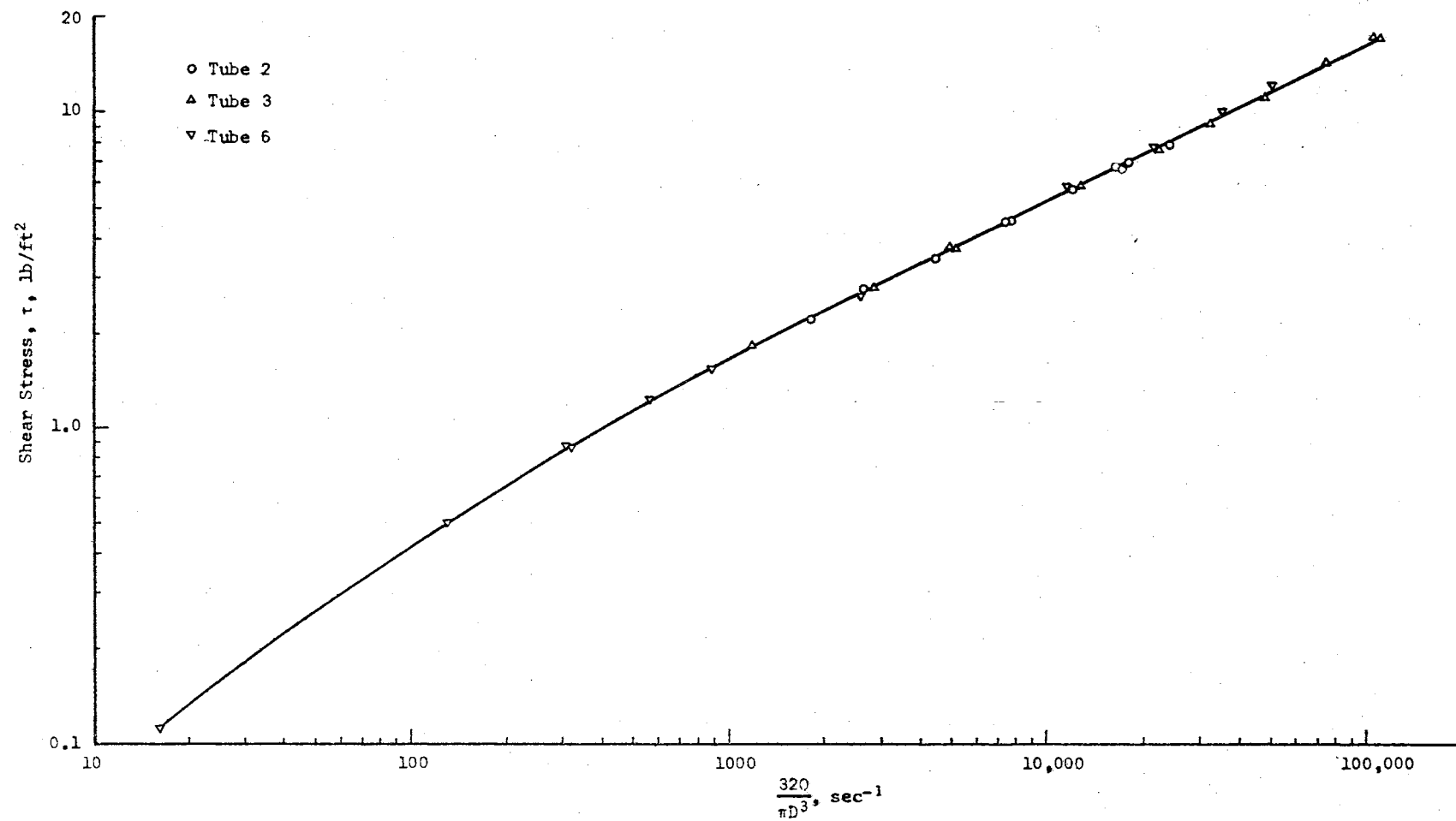


Figure 18. Flow Curve for 1% CMC Solution at 100°F

polynomial using regression analysis of the data. From the fitted equation, n' can be evaluated at each data point by differentiation and substitution. Using these values of n' and $32Q/\pi D^3$, Equation 24 can be used to calculate the true shear rate at the wall of the capillary tube, $(-dv/dr)_w$. Apparent viscosity, μ_a , can be calculated from the ratio of shear stress to true shear rate. Figure 19 is a plot of true shear rate versus apparent viscosity for the 1 percent CMC solution at 75°F from runs in tubes 3 and 6. This material was then stored in a sealed container for one month and was run again. There was no discernible difference in the sample. Pipe loop and capillary tube data of Dodge (8, 9) and capillary tube data of Craig (6) working with CMC solutions in the range of 0.3-3.0 percent show good agreement with the characteristic shape of the CMC curve of this work.

Samples of 1 1/2 percent CMC, designated by numbers 12, 19, 23, and 24, were run at various temperatures to check degradation of the original formulation and also determine the viscosity-temperature dependence of the material. Sample 12 represents a relatively new batch of prepared material in terms of its shear history. Sample 19 is the same batch as sample 12 after being subjected to many hours of pumping through the pipe loop. Samples 23 and 24 are batches that were reconstituted to approximately original consistency by adding more CMC to the solution. Figure 20 is a comparison of the flow curves for samples 12 and 19 at 100°F and shows that sample 19 is significantly thinner than sample 12.

Samples 19 and 23 were each run at four different temperatures, and results are shown in Figures 21 and 22, respectively. These curves show that although the viscosity changes considerably with temperature, n' can be considered almost independent of temperature for a given value

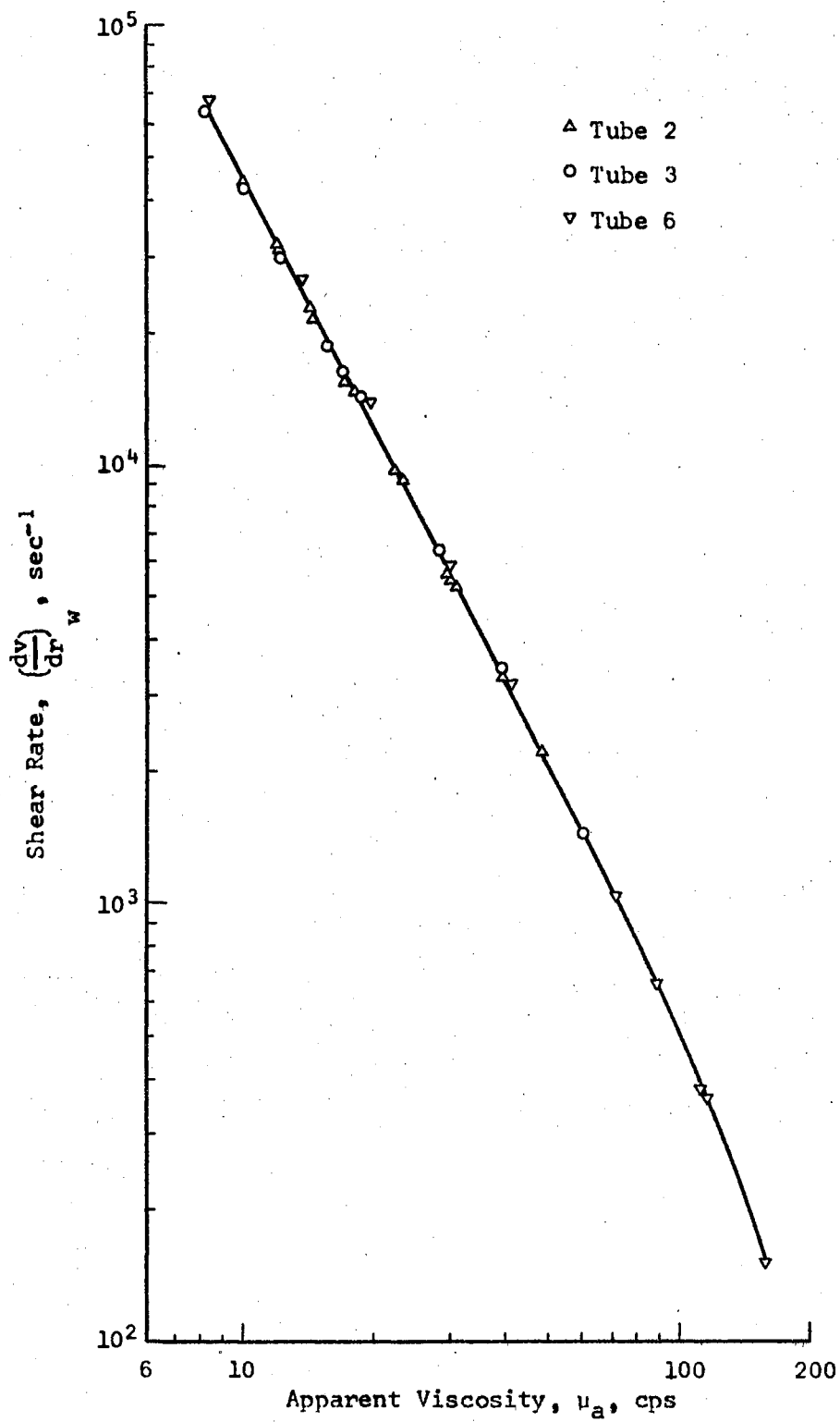


Figure 19. Logarithmic Plot of Shear Rate Versus Apparent Viscosity for 1% CMC Solution at 75°F

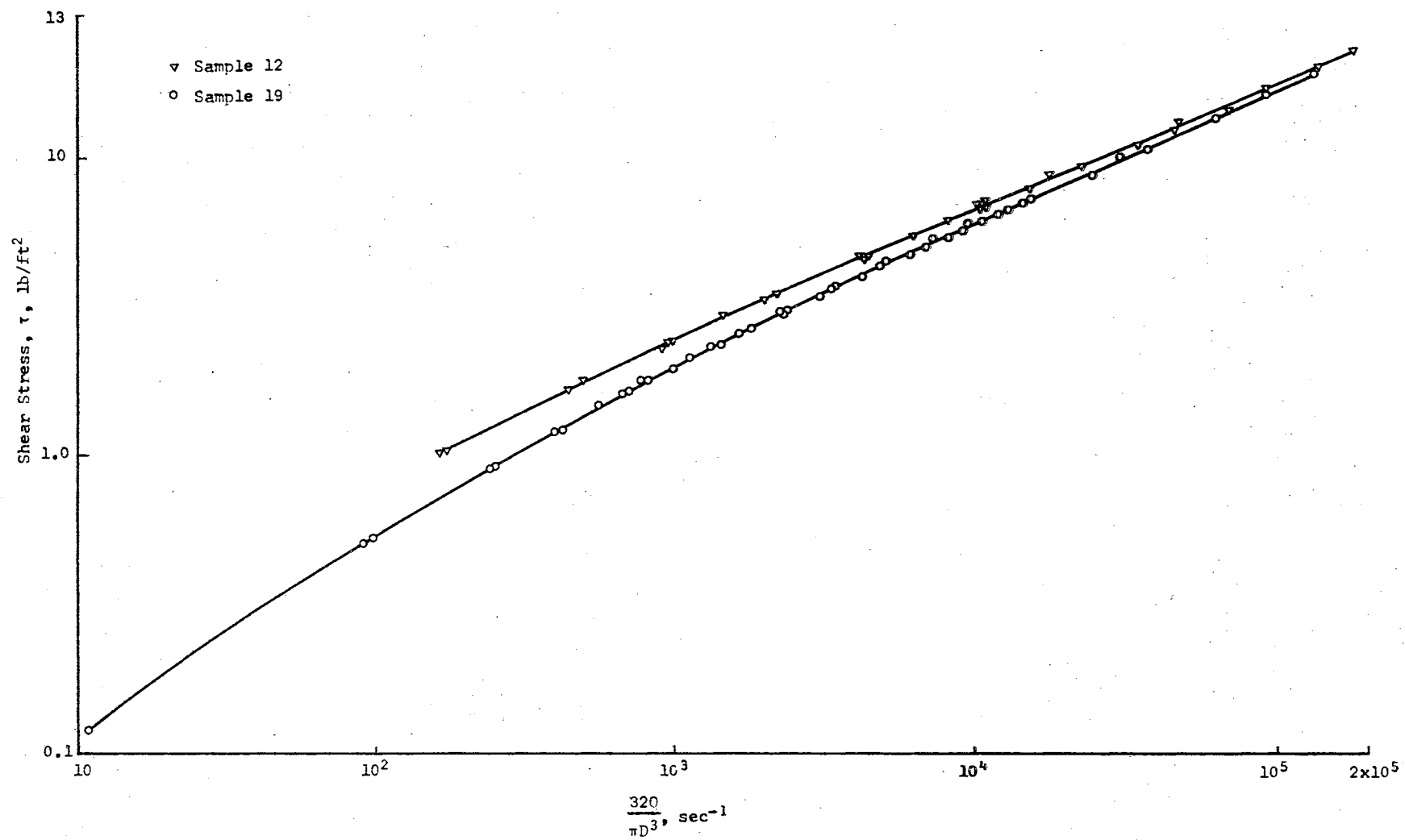


Figure 20. Comparison of Flow Curves for Samples 12 and 19 (1.5% CMC in Water) at 100°F

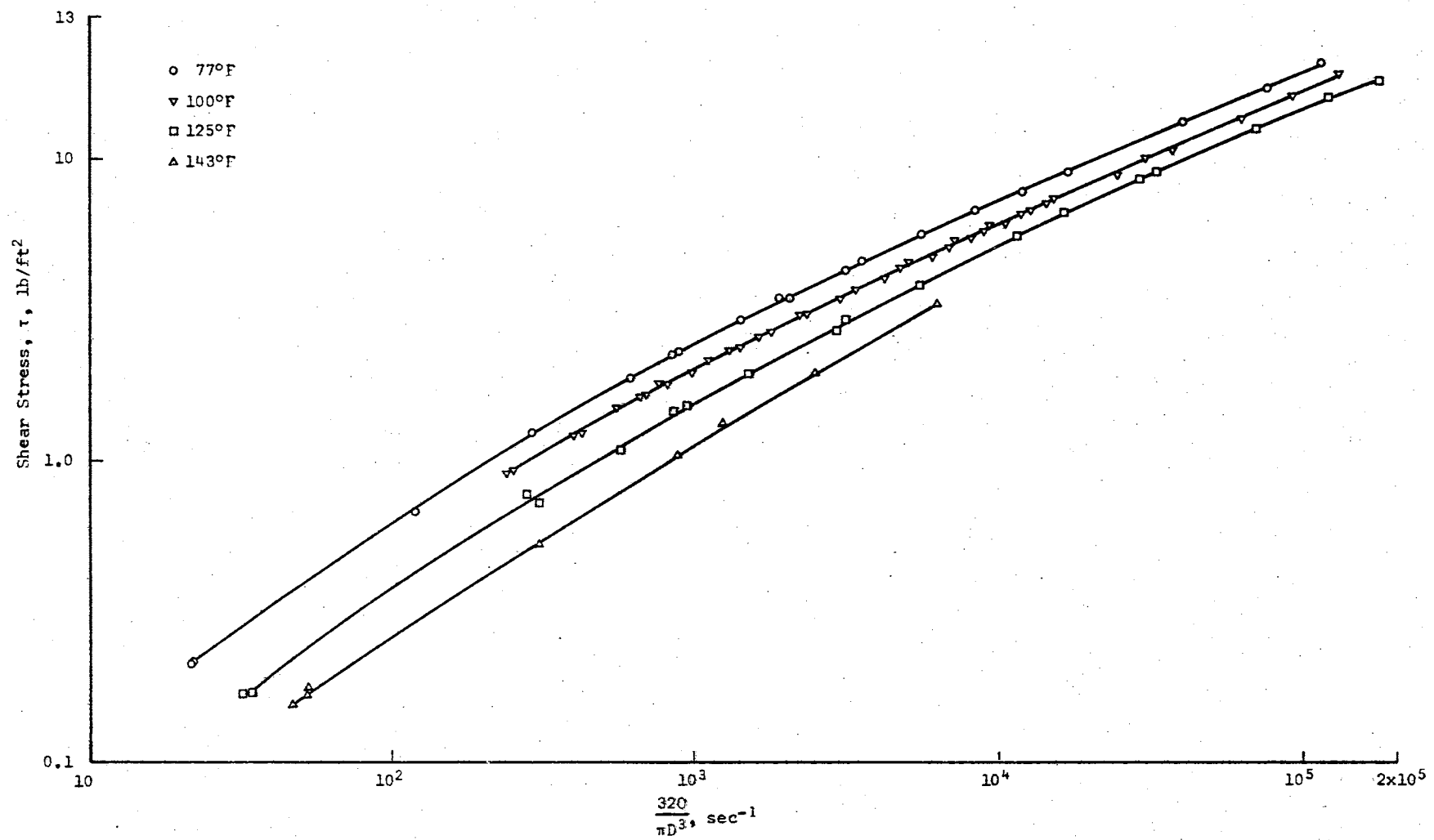


Figure 21. Effect of Temperature on the Flow Curve of Sample 19 (1.5% CMC Solution)

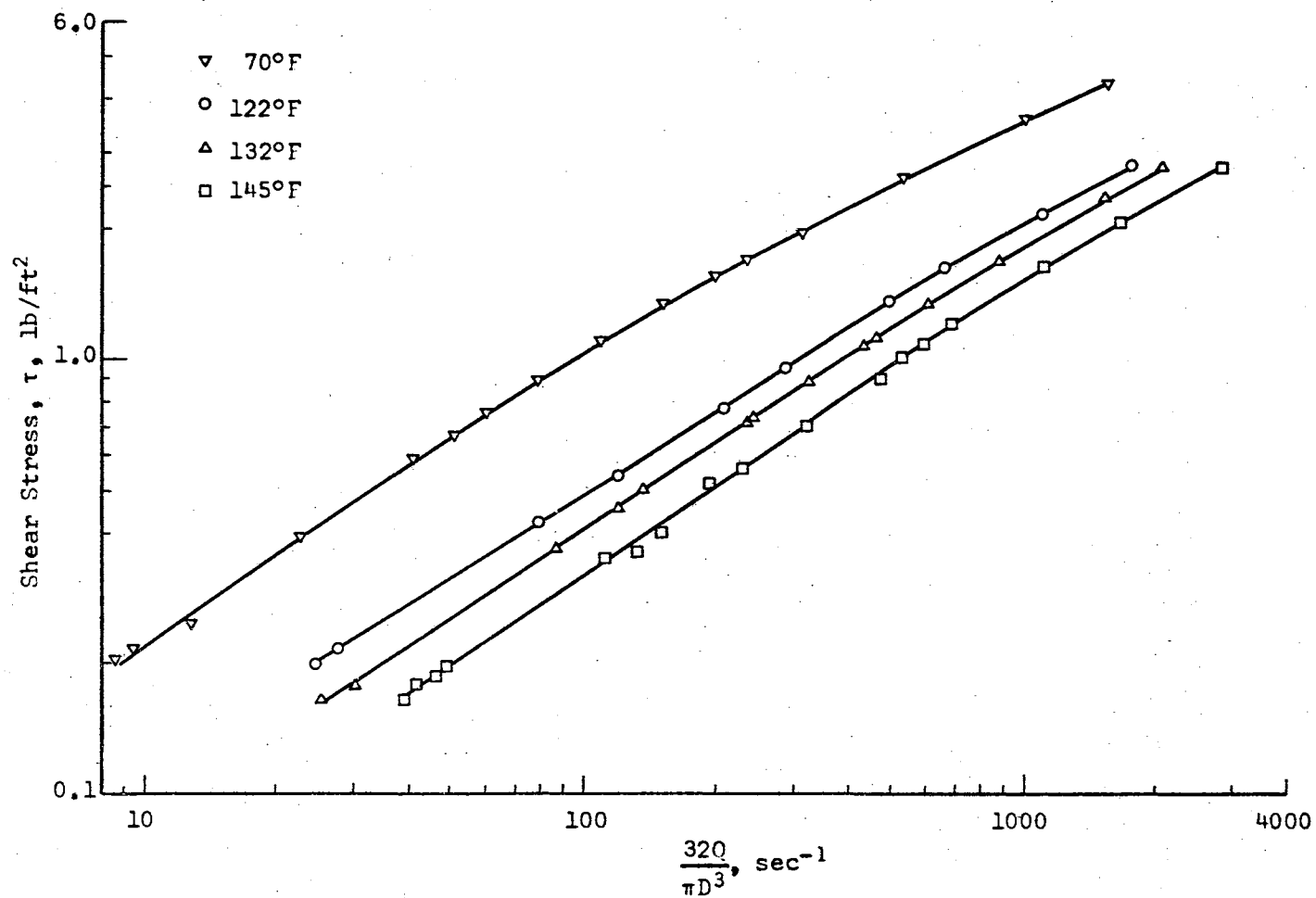


Figure 22. Temperature Dependence of Flow Curve for Sample 23

$32Q/\pi D^3$. Figure 23 shows typical curves obtained for sample 23 of apparent viscosity versus true shear rate for different temperatures, and Figure 24 shows apparent viscosity versus temperature for several selected shear rates. The curves in Figure 24 are not straight over the entire range of temperature tested, although a straight line is adequate over narrow ranges of temperature. Sample 24, for example, was tested over the range of 71-87°F and gave approximately straight lines for apparent viscosity versus temperature as shown by Figure 25.

A Comparison With Fann Viscometer Data

In order to show the validity of the capillary tube data, data for a 1 1/2 percent CMC solution at 86°F were compared with similar shear stress-shear rate data using a Fann VG model 35 rotational viscometer. The data from the Fann viscometer were taken by K. Ishihara (12) and are presented in Table II. These data were tabulated by means of the usual relationships for calculation of the shear rates for this instrument as outlined in Reference 22. This procedure assumes a power law fluid. As Figures 26 and 27 and Table III show, the agreement between the two viscometers in the appropriate shear rate range is very good.

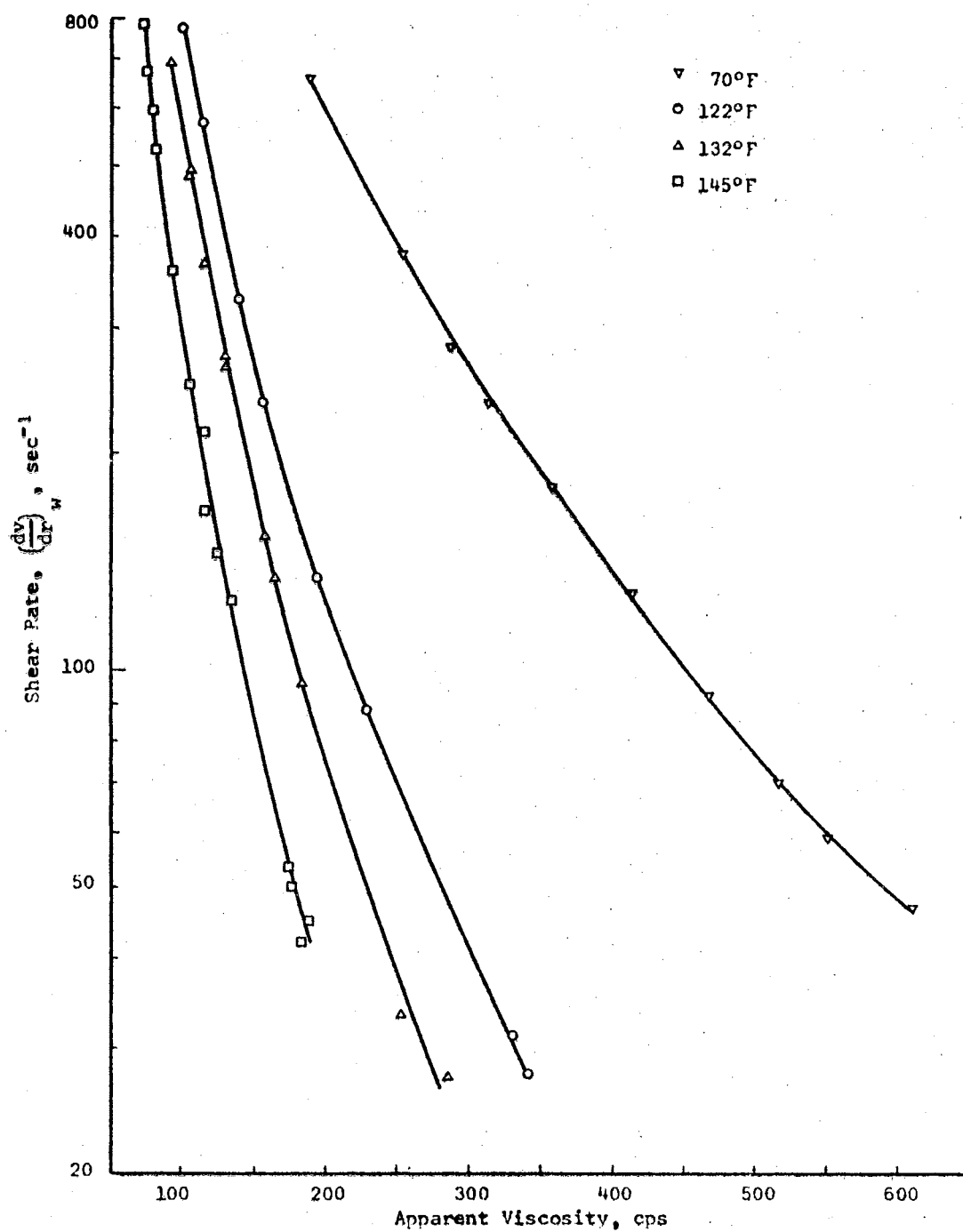


Figure 23. Apparent Viscosity of Sample 23 at Different Temperatures

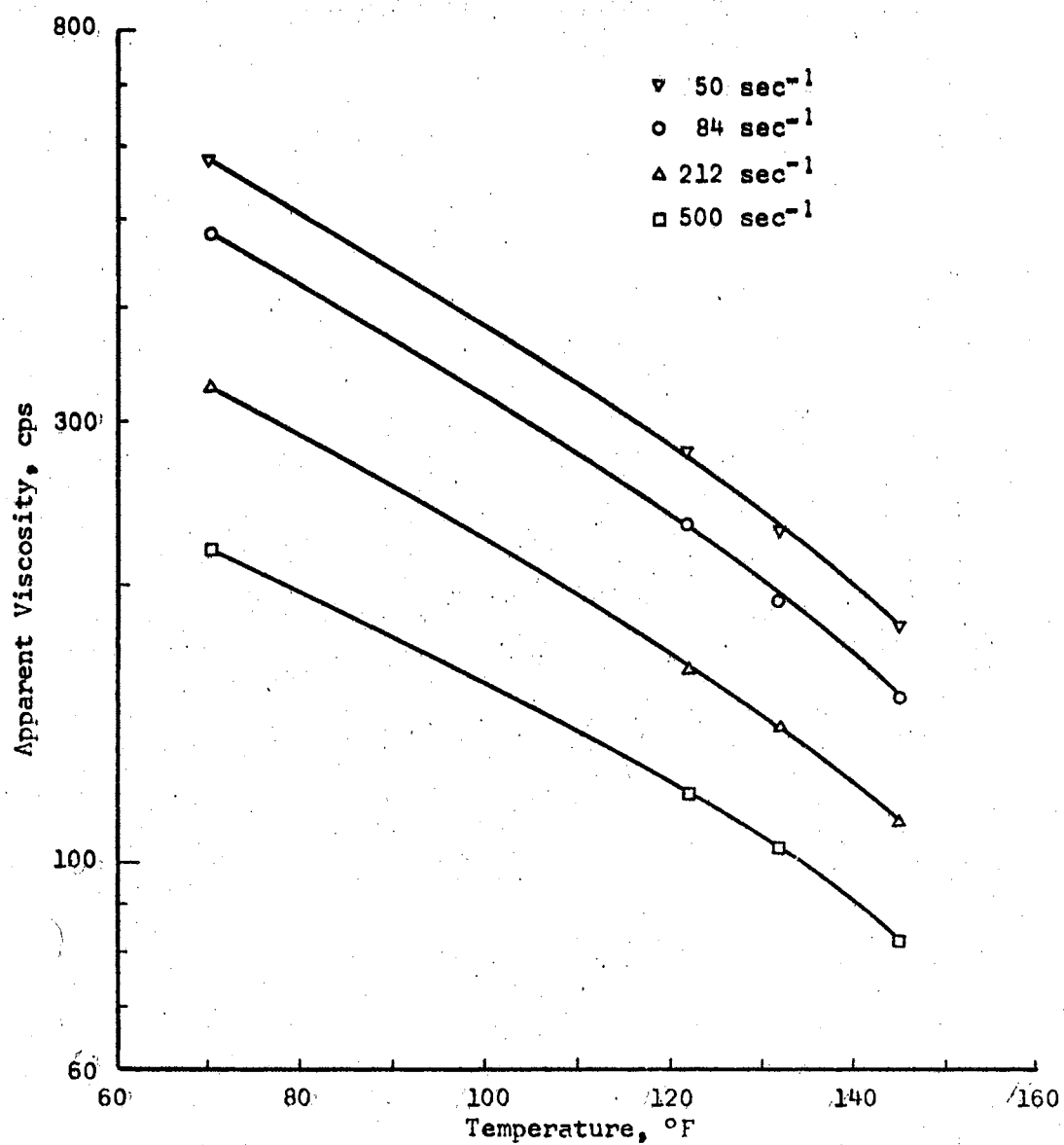


Figure 24. Apparent Viscosity Versus Temperature for Sample 23.

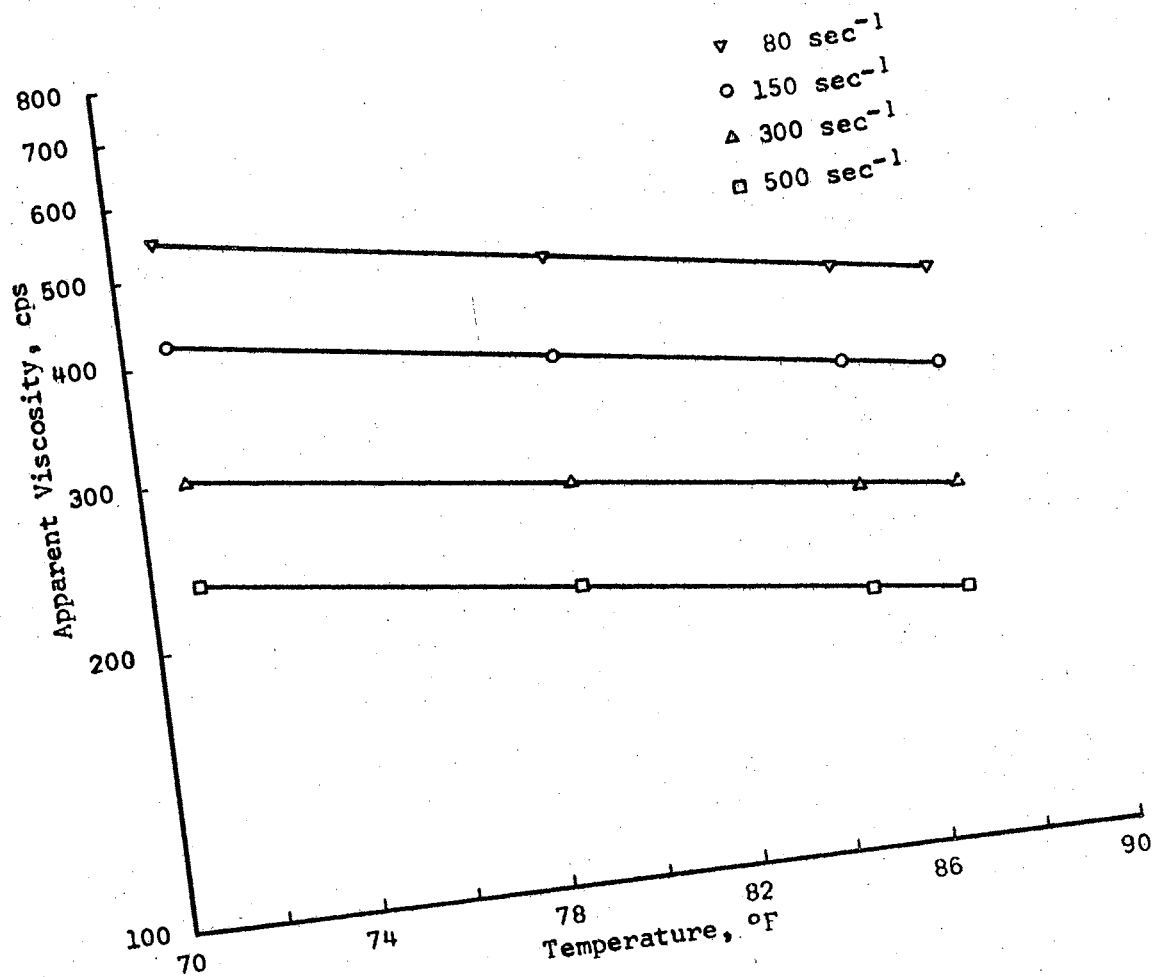


Figure 25. Apparent Viscosity Versus Temperature for Sample 24

TABLE II

FANN VISCOMETER DATA (12)

ISHIHARA SAMPLE 1 (1.5% CMC IN TAP WATER) AT 86°F

<u>SPEED (RPM)</u>	<u>DEFLECTION</u>	<u>SHEAR STRESS τ (dynes/cm²)</u>	<u>SHEAR RATE (sec⁻¹)</u>	<u>K</u>	<u>GAMMA (poise)</u>	<u>SHEAR STRESS τ (lb_f/ft²)</u>
300	222.5	1018	534	25.617	11.922	2.13
200	177.0	810	356	25.848	12.029	1.695
100	117.0	535	178	25.654	11.939	1.120

ISHIHARA SAMPLE 8 (1.5% CMC IN TAP WATER) AT 86°F

<u>SPEED (RPM)</u>	<u>DEFLECTION</u>	<u>SHEAR STRESS τ (dynes/cm²)</u>	<u>SHEAR RATE (sec⁻¹)</u>	<u>K</u>	<u>GAMMA (poise)</u>	<u>SHEAR STRESS τ (lb_f/ft²)</u>
300	231.0	1057	535	28.083	12.855	2.18
200	183.0	838	357	28.118	12.871	1.745
100	122.5	561	178	28.089	12.857	1.157

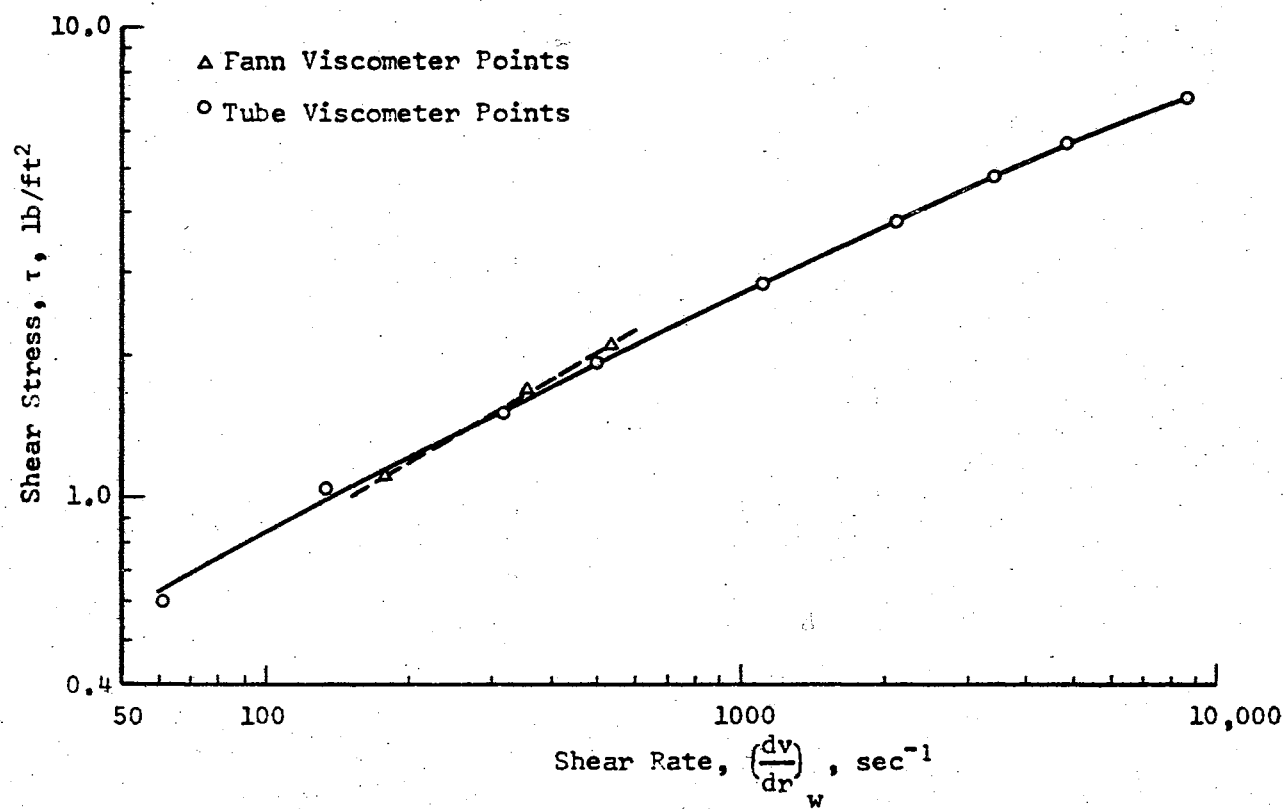


Figure 26. Comparison of Rotational and Tube Viscometer Data for Ishihara Sample No. 1 (1.5% CMC in Water) at 86°F

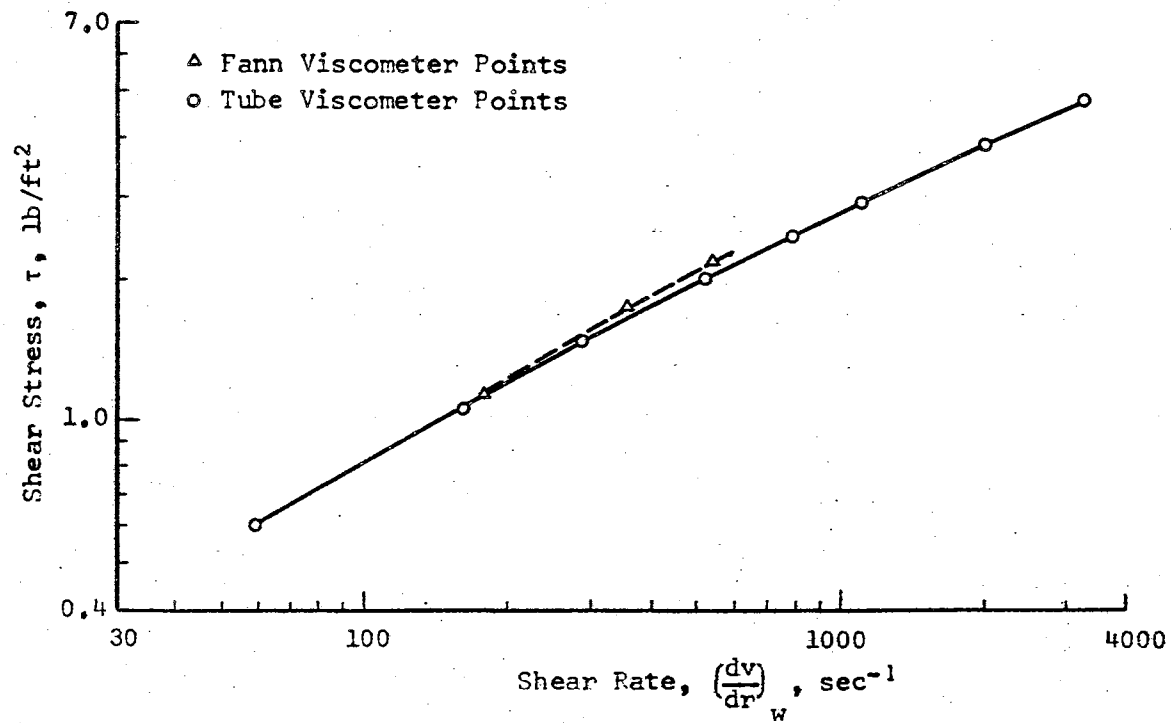


Figure 27. Comparison of Rotational and Tube Viscometer Data for Ishihara Sample No. 8 (1.5% CMC in Water) at 86°F

TABLE III

COMPARISON OF ROTATIONAL AND TUBE VISCOMETER DATA

ISHIHARA SAMPLE 1 AT 86°F

<u>SHEAR RATE (sec⁻¹)</u>	<u>FANN SHEAR STRESS (lb_f/ft²)</u>	<u>TUBE SHEAR STRESS (lb_f/ft²)</u>	<u>SHEAR STRESS % DIFF. FROM TUBE DATA</u>	<u>FANN μ_a (centipoise)</u>	<u>TUBE μ_a (centipoise)</u>	<u>μ_a % DIFF. FROM TUBE DATA</u>
178	1.120	1.130	-0.88	301	304	-0.99
356	1.695	1.650	+2.73	228	222	+2.70
534	2.13	2.02	+5.44	191	181	+5.52

ISHIHARA SAMPLE 8 AT 86°F

<u>SHEAR RATE (sec⁻¹)</u>	<u>FANN SHEAR STRESS (lb_f/ft²)</u>	<u>TUBE SHEAR STRESS (lb_f/ft²)</u>	<u>SHEAR STRESS % DIFF. FROM TUBE DATA</u>	<u>FANN μ_a (centipoise)</u>	<u>TUBE μ_a (centipoise)</u>	<u>μ_a % DIFF. FROM TUBE DATA</u>
178	1.157	1.140	+1.49	310	307	+0.98
357	1.745	1.670	+4.49	234	224	+4.47
535	2.18	2.05	+6.34	195	184	+5.98

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This capillary viscometer gave consistent calibration results for tubes of different length and different diameter using several different Newtonian calibration fluids. It is possible to obtain reproducible flow data for a non-Newtonian fluid from the instrument.

The viscometer is quite flexible in application and simple in operation. It is possible to obtain data over a five-decade range of shear rate from 10 sec^{-1} to greater than $100,000 \text{ sec}^{-1}$.

Good agreement between Fann rotational viscometer data and capillary tube data was obtained from 1 1/2 percent CMC solution in the range of $300\text{--}1,000 \text{ sec}^{-1}$ shear rate.

Recommendations

It is recommended that a quick-disconnect high-pressure hose be connected from the control panel to viscometer reservoir for greater operating convenience in removal of the top cap from the reservoir for thorough cleaning. A larger hole should be tapped in the top cap to provide easier loading of material without the necessity of unscrewing the cap. Temperature control of the capillary tubes should be incorporated in some manner to cut down the possibility of temperature

gradients down the length of the tube. Finally, it is recommended that the possibility of using the alternate system for volumetric flow measurement be seriously considered for high flow rates, foaming fluids, or hazardous fluids. A more refined method of leveling should be used, such as a continuous length of vertical screw connected to a reversible drive motor with speed control.

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APPENDIX A
NOMENCLATURE

NOMENCLATURE

- C_p - Specific heat
- D - Tube diameter
- f - Fanning friction factor or "function of"
- g_c - Conversion factor, $32.2 \text{ (lb}_m\text{-ft.)/(lb}_f\text{-sec.}^2\text{)}$
- k - Consistency index for power law equation
- k' - Consistency index for generalized equation
- K_1 - Defined by Equation 48
- K_2 - Tube correction constant
- L - Tube length
- L' - Equivalent tube length
- ΔL - Change in length
- M - Energy dissipated into heat by fluid flow
- m - Empirical kinetic energy correction factor
- N - Empirical end effects correction coefficient
- n - Flow behavior index for the power law equation
- n' - Flow behavior index for generalized equation
- P - Gauge pressure
- ΔP - Pressure drop
- $\Delta P'$ - Corrected pressure drop
- Q - Volumetric flow rate
- R - Tube radius
- r - Radial distance
- Re - Metzner-Reed generalized Reynolds number
- Re' - Weltmann Reynolds number
- T - Temperature

- t - Time
- V - Volume
- v - Local velocity of fluid
- v_m - Mean velocity of fluid
- $\frac{dv}{dr}$ - Shear rate
- $\left(\frac{dv}{dr}\right)_w$ - Shear rate at tube wall
- τ - Shear stress
- τ_y - Yield stress
- μ - Newtonian viscosity
- μ_a - Apparent viscosity
- μ_p - Plastic viscosity
- ρ - Density
- γ - Generalized viscosity coefficient defined by Equation 35
- $\frac{32Q}{\pi D^3}$ - "Flow function" or sometimes called "pseudo-shear rate"

APPENDIX B

EXPERIMENTAL AND CALCULATED
DATA TABLES

KC 10 OIL AT 100°F

TUBE 2

P (psig)	ΔV (cc)	t (sec)	$\Delta P'$ (lb _f /ft ²)	Q (ft ³ /sec)	$\frac{\Delta P'/Q}{(\frac{lb_f \cdot sec}{ft^5})}$	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$(\frac{dv}{dr})_w$ (sec ⁻¹)	ν_a (centipoise)
294	100	68.2	42035	51.8 x 10 ⁻⁶	8.118 x 10 ⁸	13.132	33938	0.90	0.00114	44	34916	18.0
294	100	67.2	42018	52.6 x 10 ⁻⁶	7.996 x 10 ⁸	13.127	34443	0.90	0.00112	43	35435	17.7
498	100	36.2	70210	97.6 x 10 ⁻⁶	7.197 x 10 ⁸	21.934	63939	0.90	0.00108	42	65780	16.0
498	100	36.8	70261	96.0 x 10 ⁻⁶	7.322 x 10 ⁸	21.950	62897	0.90	0.00109	42	64708	16.2
399	100	47.4	56639	74.5 x 10 ⁻⁶	7.603 x 10 ⁸	17.694	48831	0.90	0.00110	42	50237	16.9
399	100	46.6	56602	75.8 x 10 ⁻⁶	7.469 x 10 ⁸	17.683	49669	0.90	0.00109	42	51100	16.6
399	100	47.1	56620	75.0 x 10 ⁻⁶	7.551 x 10 ⁸	17.689	49142	0.90	0.00110	42	50557	16.8
202	100	100.1	29012	35.3 x 10 ⁻⁶	8.223 x 10 ⁸	9.064	23123	0.90	0.00111	43	23789	18.2
200	100	100.8	28725	35.0 x 10 ⁻⁶	8.200 x 10 ⁸	8.974	22962	0.90	0.00110	43	23623	18.2
151	100	134.7	21760	26.2 x 10 ⁻⁶	8.299 x 10 ⁸	6.798	17183	0.90	0.00108	42	17678	18.4
151	100	133.5	21755	26.5 x 10 ⁻⁶	8.225 x 10 ⁸	6.796	17338	0.90	0.00107	41	17837	18.2
100	40	84.1	14482	16.8 x 10 ⁻⁶	8.620 x 10 ⁸	4.524	11009	0.90	0.00108	42	11326	19.1
100	40	81.5	14477	17.3 x 10 ⁻⁶	8.354 x 10 ⁸	4.523	11360	0.90	0.00105	40	11687	18.5
100	40	83.4	14478	16.9 x 10 ⁻⁶	8.547 x 10 ⁸	4.523	11101	0.90	0.00107	41	11421	19.0
100	40	81.8	14475	17.3 x 10 ⁻⁶	8.382 x 10 ⁸	4.522	11318	0.90	0.00105	40	11644	18.6
76.0	40	112.1	11042	12.6 x 10 ⁻⁶	8.763 x 10 ⁸	3.450	8259	0.90	0.00106	41	8497	19.4
76.0	40	109.2	11040	12.9 x 10 ⁻⁶	8.532 x 10 ⁸	3.449	8478	0.90	0.00104	40	8723	18.9
50.0	30	125.2	7311	8.5 x 10 ⁻⁶	8.642 x 10 ⁸	2.284	5546	0.90	0.00100	39	5706	19.2
50.0	30	125.2	7310	8.4 x 10 ⁻⁶	8.661 x 10 ⁸	2.284	5533	0.90	0.00101	39	5692	19.2
125	35	58.1	18042	21.3 x 10 ⁻⁶	8.482 x 10 ⁸	5.636	13943	0.90	0.00108	42	14345	18.8
125	35	57.0	18038	21.7 x 10 ⁻⁶	8.320 x 10 ⁸	5.635	14212	0.90	0.00107	41	14622	18.5
39.8	30	156.4	5842	6.8 x 10 ⁻⁶	8.629 x 10 ⁸	1.825	4440	0.90	0.00098	38	4568	19.1
39.8	20	106.6	5842	6.6 x 10 ⁻⁶	8.811 x 10 ⁸	1.825	4343	0.90	0.00100	39	4468	19.6
39.6	30	160.4	5812	6.6 x 10 ⁻⁶	8.806 x 10 ⁸	1.816	4329	0.90	0.00100	38	4454	19.5

KC 10 OIL AT 100°F

TUBE 3

P (psig)	AV (cc)	t (sec)	$\Delta P'$ (lb _f /ft ²)	Q (ft ³ /sec)	$\frac{\Delta P' / O}{\left(\frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^5}\right)}$	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
150	25	45.8	21730	19.3 x 10 ⁻⁶	11.27 x 10 ⁸	5.416	12634	0.95	0.00067	29	12792	20.3
150	40	71.2	21725	19.8 x 10 ⁻⁶	10.95 x 10 ⁸	5.415	13003	0.95	0.00065	28	13166	19.7
150	40	70.5	21723	20.0 x 10 ⁻⁶	10.84 x 10 ⁸	5.414	13132	0.95	0.00065	28	13297	19.5
200	45	57.6	28858	27.6 x 10 ⁻⁶	10.46 x 10 ⁸	7.193	18083	0.95	0.00064	28	18309	18.8
200	50	64.1	28857	27.6 x 10 ⁻⁶	10.47 x 10 ⁸	7.193	18055	0.95	0.00064	28	18280	18.8
200	50	63.1	28852	28.0 x 10 ⁻⁶	10.31 x 10 ⁸	7.191	18341	0.95	0.00063	27	18570	18.5
304	80	64.9	43631	43.5 x 10 ⁻⁶	10.02 x 10 ⁸	10.875	28531	0.95	0.00062	27	28888	18.0
304	80	63.5	43614	44.5 x 10 ⁻⁶	9.803 x 10 ⁸	10.871	29160	0.95	0.00061	26	29525	17.6
252	70	69.9	36250	35.4 x 10 ⁻⁶	10.25 x 10 ⁸	9.035	23179	0.95	0.00063	27	23469	18.4
252	70	67.9	36235	36.4 x 10 ⁻⁶	9.952 x 10 ⁸	9.032	23862	0.95	0.00061	27	24160	17.9
176	40	57.9	25417	24.4 x 10 ⁻⁶	10.42 x 10 ⁸	6.335	15990	0.95	0.00063	27	16190	18.7
176	25	34.8	25407	25.4 x 10 ⁻⁶	10.01 x 10 ⁸	6.333	16628	0.95	0.00061	26	16836	18.0
125	40	81.7	18122	17.3 x 10 ⁻⁶	10.48 x 10 ⁸	4.517	11332	0.95	0.00062	27	11474	18.9
125	40	79.0	18118	17.9 x 10 ⁻⁶	10.13 x 10 ⁸	4.516	11719	0.95	0.00060	26	11866	18.2
100	30	77.2	14539	13.7 x 10 ⁻⁶	10.60 x 10 ⁸	3.624	8995	0.95	0.00062	27	9107	19.0
100	40	101.1	14537	14.0 x 10 ⁻⁶	10.41 x 10 ⁸	3.623	9158	0.95	0.00061	26	9272	18.7
100	75	193.2	14536	13.7 x 10 ⁻⁶	10.60 x 10 ⁸	3.623	8985	0.95	0.00062	27	9098	19.1
100	70	178.2	14533	13.9 x 10 ⁻⁶	10.48 x 10 ⁸	3.622	9092	0.95	0.00062	27	9206	18.8
76.0	20	70.5	11092	10.0 x 10 ⁻⁶	11.07 x 10 ⁸	2.765	6566	0.95	0.00064	28	6648	19.9
76.0	20	67.1	11089	10.5 x 10 ⁻⁶	10.53 x 10 ⁸	2.764	6899	0.95	0.00061	26	6985	18.9
76.0	20	68.6	11090	10.3 x 10 ⁻⁶	10.77 x 10 ⁸	2.764	6748	0.95	0.00062	27	6832	19.4
76.0	90	300.0	11087	10.6 x 10 ⁻⁶	10.47 x 10 ⁸	2.763	6944	0.95	0.00061	26	7031	18.8
50.0	30	159.2	7353	6.7 x 10 ⁻⁶	11.06 x 10 ⁸	1.833	4362	0.95	0.00063	27	4416	19.9
50.0	30	160.6	7352	6.6 x 10 ⁻⁶	11.14 x 10 ⁸	1.832	4324	0.95	0.00063	27	4378	20.0
50.0	50	261.8	7350	6.7 x 10 ⁻⁶	10.91 x 10 ⁸	1.832	4421	0.95	0.00062	27	4476	19.6
125	50	97.6	18098	18.1 x 10 ⁻⁶	10.00 x 10 ⁸	4.511	11858	0.95	0.00060	26	12006	18.0
125	50	99.5	18099	17.8 x 10 ⁻⁶	10.20 x 10 ⁸	4.511	11631	0.95	0.00061	26	11777	18.3
125	50	98.8	18096	17.9 x 10 ⁻⁶	10.13 x 10 ⁸	4.510	11714	0.95	0.00060	26	11860	18.2
125	75	147.8	18094	17.9 x 10 ⁻⁶	10.10 x 10 ⁸	4.510	11745	0.95	0.00060	26	11892	18.2
125	40	79.0	18091	17.9 x 10 ⁻⁶	10.12 x 10 ⁸	4.509	11719	0.95	0.00060	26	11866	18.2

KC 10 OIL AT 100°F

TUBE 5

P (psig)	ΔV (cc)	t (sec)	$\Delta P'$ (lb _f /ft ²)	Q (ft ³ /sec)	$\frac{\Delta P' / Q}{\left(\frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^5}\right)}$	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	ν_a (centipoise)
150	200	14.6	20373	484 × 10 ⁻⁶	4.211 × 10 ⁷	13.210	35247	0.96	0.00059	26	35648	17.7
150	300	21.0	20242	504 × 10 ⁻⁶	4.012 × 10 ⁷	13.126	36758	0.96	0.00056	25	37176	16.9
125	200	16.4	17041	431 × 10 ⁻⁶	3.957 × 10 ⁷	11.050	31378	0.96	0.00055	24	31735	16.7
101	200	20.4	13966	346 × 10 ⁻⁶	4.034 × 10 ⁷	9.056	25226	0.96	0.00056	24	25513	17.0
75.0	200	27.6	10538	256 × 10 ⁻⁶	4.118 × 10 ⁷	6.833	18645	0.96	0.00056	25	18857	17.4
75.0	175	23.5	10511	263 × 10 ⁻⁶	3.997 × 10 ⁷	6.815	19161	0.96	0.00055	24	19379	16.8
50.0	100	21.6	7158	163 × 10 ⁻⁶	4.378 × 10 ⁷	4.642	11912	0.96	0.00059	26	12048	18.4
25.0	40	17.2	3675	82.1 × 10 ⁻⁶	4.475 × 10 ⁷	2.383	5984	0.96	0.00058	25	6052	18.9
25.0	40	17.6	3675	80.3 × 10 ⁻⁶	4.579 × 10 ⁷	2.383	5848	0.96	0.00060	26	5914	19.3
10.0	20	22.2	1547	31.8 × 10 ⁻⁶	4.863 × 10 ⁷	1.003	2318	0.96	0.00061	27	2344	20.5

KC 10 OIL AT 100°F

TUBE 6

150	200	17.6	20982	401 × 10 ⁻⁶	5.229 × 10 ⁷	10.941	29071	0.92	0.00085	35	29700	17.6
100	200	25.6	14198	276 × 10 ⁻⁶	5.146 × 10 ⁷	7.404	19986	0.92	0.00082	33	20419	17.4
75.0	130	22.8	10770	201 × 10 ⁻⁶	5.349 × 10 ⁷	5.616	14586	0.92	0.00083	34	14902	18.0
49.0	100	27.0	7139	131 × 10 ⁻⁶	5.458 × 10 ⁷	3.723	9475	0.92	0.00082	33	9680	18.4
49.0	200	52.6	7130	134 × 10 ⁻⁶	5.310 × 10 ⁷	3.718	9727	0.92	0.00080	32	9938	17.9
41.0	200	65.1	6004	108 × 10 ⁻⁶	5.534 × 10 ⁷	3.131	7859	0.92	0.00082	33	8030	18.7
30.5	70	30.3	4513	81.6 × 10 ⁻⁶	5.532 × 10 ⁷	2.353	5910	0.92	0.00080	32	6038	18.7
30.5	70	30.0	4510	82.4 × 10 ⁻⁶	5.473 × 10 ⁷	2.352	5969	0.92	0.00079	32	6099	18.5
20.2	70	46.0	3044	53.7 × 10 ⁻⁶	5.664 × 10 ⁷	1.587	3893	0.92	0.00079	32	3977	19.1
20.2	70	46.6	3042	53.1 × 10 ⁻⁶	5.734 × 10 ⁷	1.586	3843	0.92	0.00080	32	3926	19.3

NBS OIL M AT 72°F

TUBE 5

<u>P</u> (psig)	<u>ΔV</u> (cc)	<u>t</u> (sec)	<u>ΔP₁</u> (lb _f /ft ²)	<u>Q</u> (ft ³ /sec)	<u>τ</u> (lb _f /ft ²)	<u>($\frac{dv}{dr}$)</u> (sec ⁻¹)	<u>μ_a</u> (centipoise)
24.3	40	255.93	3607	5.51 × 10 ⁻⁶	2.360	393	288
49.5	50	162.83	7237	10.8 × 10 ⁻⁶	4.725	770	294
104.0	40	62.22	15091	22.7 × 10 ⁻⁶	9.86	1620	291
14.5	20	214.30	2194	3.29 × 10 ⁻⁶	1.434	235	292
75.5	40	84.31	10980	16.8 × 10 ⁻⁶	7.18	1198	287
154.0	50	51.59	22292	34.2 × 10 ⁻⁶	14.58	2460	284

NBS OIL M AT 74°F

TUBE 8

75.8	60	9.18	10981	231 × 10 ⁻⁶	13.50	2480	260
0.1	8	112.28	119	2.51 × 10 ⁻⁶	0.1463	27	260
39.5	35	10.17	5780	122 × 10 ⁻⁶	7.11	1308	260
10.7	20	20.67	1643	34.2 × 10 ⁻⁶	2.025	367	264
5.5	20	35.93	894	19.7 × 10 ⁻⁶	1.098	211	267
20.7	40	21.62	3079	65.3 × 10 ⁻⁶	3.78	701	258
2.7	20	67.54	490	10.5 × 10 ⁻⁶	0.602	112	257

NBS OIL M AT 74°F

TUBE 11

0.0	20	101.60	115	6.96 × 10 ⁻⁶	0.1840	34	261
15.2	70	18.02	2292	137 × 10 ⁻⁶	3.66	666	263
5.2	40	27.49	852	51.4 × 10 ⁻⁶	1.363	250	262
10.1	70	25.91	1552	95.4 × 10 ⁻⁶	2.48	463	256
2.8	16	18.75	501	30.1 × 10 ⁻⁶	0.802	146	263

NBS CERTIFIED VISCOSITY VALUES FOR OIL M

<u>TEMPERATURE (°F)</u>	<u>μ (centipoise)</u>
68	342.6
77	239.9
100	107.5
210	9.69

DISTILLED WATER AT 72°F

TUBE 1

P (psig)	ΔV (cc)	t (sec)	ΔP' (lb _f /ft ²)	Q (ft ³ /sec)	$\frac{\Delta P' / Q}{\left(\frac{\text{lb}_f \cdot \text{sec}}{\text{ft}^5}\right)}$	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ _a (centipoise)
0.0	40	271.6	161	5.20 × 10 ⁻⁶	3.188 × 10 ⁷	0.067	3397	0.97	2.6 × 10 ⁻⁵	1.16	3427	0.93
0.0	20	138.4	160	5.10 × 10 ⁻⁶	3.231 × 10 ⁷	0.066	3333	0.97	2.6 × 10 ⁻⁵	1.17	3362	0.94
0.0	40	275.8	159	5.12 × 10 ⁻⁶	3.208 × 10 ⁷	0.066	3345	0.97	2.6 × 10 ⁻⁵	1.16	3375	0.93
0.0	45	316.0	161	5.03 × 10 ⁻⁶	3.300 × 10 ⁷	0.067	3284	0.97	2.7 × 10 ⁻⁵	1.19	3313	0.96
0.0	20	142.0	160	4.97 × 10 ⁻⁶	3.280 × 10 ⁷	0.066	3248	0.97	2.7 × 10 ⁻⁵	1.20	3277	0.97
0.0	45	319.9	159	4.97 × 10 ⁻⁶	3.260 × 10 ⁷	0.066	3244	0.97	2.7 × 10 ⁻⁵	1.20	3273	0.96

TUBE 2

0.0	20	154.8	192	4.56 × 10 ⁻⁶	4.254 × 10 ⁷	0.060	2990	0.97	2.6 × 10 ⁻⁵	1.18	3017	0.95
0.0	20	154.4	191	4.57 × 10 ⁻⁶	4.237 × 10 ⁷	0.060	2998	0.97	2.6 × 10 ⁻⁵	1.17	3025	0.95
0.0	20	155.4	190	4.54 × 10 ⁻⁶	4.313 × 10 ⁷	0.060	2979	0.97	2.6 × 10 ⁻⁵	1.17	3005	0.95
0.0	20	152.8	192	4.62 × 10 ⁻⁶	4.265 × 10 ⁷	0.060	3030	0.97	2.6 × 10 ⁻⁵	1.16	3056	0.94
0.0	20	155.6	192	4.54 × 10 ⁻⁶	4.340 × 10 ⁷	0.060	2975	0.97	2.6 × 10 ⁻⁵	1.18	3001	0.96

TUBE 3

0.0	20	168.3	225	4.20 × 10 ⁻⁶	5.440 × 10 ⁷	0.056	2751	0.97	2.7 × 10 ⁻⁵	1.19	2775	0.97
0.0	20	169.2	225	4.17 × 10 ⁻⁶	5.421 × 10 ⁷	0.056	2736	0.97	2.7 × 10 ⁻⁵	1.20	2760	0.97
0.0	20	170.4	224	4.14 × 10 ⁻⁶	5.534 × 10 ⁷	0.056	2717	0.97	2.7 × 10 ⁻⁵	1.20	2741	0.97
0.0	20	171.6	226	4.12 × 10 ⁻⁶	5.485 × 10 ⁷	0.056	2698	0.97	2.7 × 10 ⁻⁵	1.22	2722	0.99
0.0	20	172.4	225	4.10 × 10 ⁻⁶	5.488 × 10 ⁷	0.056	2685	0.97	2.7 × 10 ⁻⁵	1.22	2709	0.99
0.0	20	173.4	224	4.07 × 10 ⁻⁶	5.504 × 10 ⁷	0.056	2670	0.97	2.7 × 10 ⁻⁵	1.22	2693	0.99
0.0	20	242.3	155	2.91 × 10 ⁻⁶	5.410 × 10 ⁷	0.039	1911	0.97	2.6 × 10 ⁻⁵	1.17	1927	0.96

TUBE 5

0.0	150	72.9	156	72.7 × 10 ⁻⁶	2.659 × 10 ⁶	0.102	5170	0.97	2.6 × 10 ⁻⁵	1.18	5215	0.94
0.0	100	53.3	144	66.3 × 10 ⁻⁶	2.641 × 10 ⁶	0.094	4714	0.97	2.7 × 10 ⁻⁵	1.19	4756	0.95
0.0	100	58.4	131	60.5 × 10 ⁻⁶	2.594 × 10 ⁶	0.086	4302	0.97	2.7 × 10 ⁻⁵	1.18	4340	0.94
0.0	100	48.8	157	72.4 × 10 ⁻⁶	2.675 × 10 ⁶	0.102	5148	0.97	2.7 × 10 ⁻⁵	1.17	5124	0.94
0.0	100	54.0	144	65.4 × 10 ⁻⁶	2.661 × 10 ⁶	0.094	4653	0.97	2.7 × 10 ⁻⁵	1.20	4694	0.96
0.0	150	88.0	133	60.2 × 10 ⁻⁶	2.631 × 10 ⁶	0.087	4283	0.97	2.7 × 10 ⁻⁵	1.20	4321	0.96
0.0	102	64.4	119	55.9 × 10 ⁻⁶	2.521 × 10 ⁶	0.078	3979	0.97	2.6 × 10 ⁻⁵	1.16	4015	0.93
0.0	100	70.7	108	50.0 × 10 ⁻⁶	2.524 × 10 ⁶	0.071	3554	0.97	2.6 × 10 ⁻⁵	1.18	3585	0.95

DISTILLED WATER AT 72°F

TUBE 4

P (psig)	ΔV (cc)	t (sec)	$\Delta P'$ (lb _f /ft ²)	Q (ft ³ /sec)	$\frac{\Delta P' / Q}{\left(\frac{\text{lb}_f\text{-sec}}{\text{ft}^5}\right)}$	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
0.0	150	73.3	134	72.3 x 10 ⁻⁶	2.227 x 10 ⁶	0.113	5615	0.97	2.7 x 10 ⁻⁵	1.21	5665	0.96
0.0	100	54.0	119	65.4 x 10 ⁻⁶	2.158 x 10 ⁶	0.101	5081	0.97	2.7 x 10 ⁻⁵	1.19	5126	0.94
0.0	100	61.8	104	57.1 x 10 ⁻⁶	2.117 x 10 ⁶	0.088	4440	0.97	2.6 x 10 ⁻⁵	1.18	4479	0.94
0.0	100	68.7	94	51.4 x 10 ⁻⁶	2.087 x 10 ⁶	0.079	3994	0.97	2.6 x 10 ⁻⁵	1.18	4029	0.94
0.0	90	70.0	84	45.4 x 10 ⁻⁶	2.088 x 10 ⁶	0.071	3528	0.97	2.7 x 10 ⁻⁵	1.19	3559	0.96
0.0	150	72.3	134	73.3 x 10 ⁻⁶	2.204 x 10 ⁶	0.113	5693	0.97	2.7 x 10 ⁻⁵	1.19	5743	0.94
0.0	100	53.2	121	66.4 x 10 ⁻⁶	2.167 x 10 ⁶	0.103	5158	0.97	2.7 x 10 ⁻⁵	1.19	5203	0.94
0.0	100	59.0	109	59.9 x 10 ⁻⁶	2.123 x 10 ⁶	0.092	4651	0.97	2.6 x 10 ⁻⁵	1.18	4692	0.94
0.0	100	66.7	96	52.9 x 10 ⁻⁶	2.088 x 10 ⁶	0.081	4114	0.97	2.6 x 10 ⁻⁵	1.17	4150	0.94
0.0	90	62.1	94	51.2 x 10 ⁻⁶	2.098 x 10 ⁶	0.079	3977	0.97	2.7 x 10 ⁻⁵	1.18	4012	0.95
0.0	60	43.0	91	49.3 x 10 ⁻⁶	2.108 x 10 ⁶	0.077	3829	0.97	2.7 x 10 ⁻⁵	1.20	3863	0.96
0.0	35	25.0	89	49.4 x 10 ⁻⁶	2.051 x 10 ⁶	0.076	3841	0.97	2.6 x 10 ⁻⁵	1.16	3875	0.93
0.0	90	66.2	88	48.0 x 10 ⁻⁶	2.079 x 10 ⁶	0.074	3730	0.97	2.6 x 10 ⁻⁵	1.18	3763	0.95
0.0	90	68.7	84	46.3 x 10 ⁻⁶	2.062 x 10 ⁶	0.071	3595	0.97	2.6 x 10 ⁻⁵	1.17	3626	0.94

TUBE 5

0.0	80	43.83	184	64.5 x 10 ⁻⁶	3.449 x 10 ⁶	0.096	4635	0.97	2.8 x 10 ⁻⁵	1.23	4676	0.98
0.0	100	54.53	179	64.8 x 10 ⁻⁶	3.364 x 10 ⁶	0.093	4657	0.97	2.7 x 10 ⁻⁵	1.19	4699	0.95
0.0	90	49.28	175	64.5 x 10 ⁻⁶	3.315 x 10 ⁶	0.091	4638	0.97	2.6 x 10 ⁻⁵	1.17	4679	0.94
0.0	100	55.92	172	63.2 x 10 ⁻⁶	3.318 x 10 ⁶	0.090	4541	0.97	2.6 x 10 ⁻⁵	1.18	4582	0.94
0.0	80	45.14	169	62.6 x 10 ⁻⁶	3.284 x 10 ⁶	0.088	4501	0.97	2.6 x 10 ⁻⁵	1.17	4541	0.93
0.0	110	63.23	166	61.4 x 10 ⁻⁶	3.280 x 10 ⁶	0.087	4418	0.97	2.6 x 10 ⁻⁵	1.17	4457	0.93
0.0	80	47.16	164	59.9 x 10 ⁻⁶	3.295 x 10 ⁶	0.086	4308	0.97	2.6 x 10 ⁻⁵	1.18	4346	0.94
0.0	110	65.91	161	58.9 x 10 ⁻⁶	3.283 x 10 ⁶	0.084	4238	0.97	2.6 x 10 ⁻⁵	1.18	4276	0.94
0.0	90	54.68	158	58.1 x 10 ⁻⁶	3.263 x 10 ⁶	0.083	4180	0.97	2.6 x 10 ⁻⁵	1.17	4217	0.94
0.0	120	74.30	155	57.0 x 10 ⁻⁶	3.250 x 10 ⁶	0.081	4102	0.97	2.6 x 10 ⁻⁵	1.17	4138	0.94
0.0	90	57.57	153	55.2 x 10 ⁻⁶	3.285 x 10 ⁶	0.080	3970	0.97	2.7 x 10 ⁻⁵	1.19	4005	0.96
0.0	120	77.68	150	54.5 x 10 ⁻⁶	3.252 x 10 ⁶	0.078	3923	0.97	2.6 x 10 ⁻⁵	1.18	3958	0.95
0.0	90	59.63	147	53.3 x 10 ⁻⁶	3.251 x 10 ⁶	0.077	3833	0.97	2.7 x 10 ⁻⁵	1.18	3867	0.95
0.0	120	81.46	144	52.0 x 10 ⁻⁶	3.248 x 10 ⁶	0.075	3741	0.97	2.7 x 10 ⁻⁵	1.19	3774	0.95
0.0	90	62.31	141	51.0 x 10 ⁻⁶	3.234 x 10 ⁶	0.074	3668	0.97	2.7 x 10 ⁻⁵	1.18	3701	0.95
0.0	100	69.89	138	50.5 x 10 ⁻⁶	3.193 x 10 ⁶	0.072	3634	0.97	2.6 x 10 ⁻⁵	1.17	3666	0.94
0.0	80	57.49	135	49.1 x 10 ⁻⁶	3.202 x 10 ⁶	0.070	3534	0.97	2.6 x 10 ⁻⁵	1.18	3565	0.95

1% CMC IN TAP WATER AT 75°F

TUBE 2

P (psig)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	ν_a (centipoise)
145	25	34.2	20939	25.8 x 10 ⁻⁶	6.541	16920	0.463	0.072	1131	21829	14.4
149	40	55.6	21517	25.4 x 10 ⁻⁶	6.722	16652	0.463	0.074	1167	21474	15.0
100	25	75.2	14548	11.7 x 10 ⁻⁶	4.545	7695	0.487	0.058	961	9724	22.4
100	35	110.6	14550	11.2 x 10 ⁻⁶	4.545	7325	0.488	0.059	975	9245	23.5
100	25	74.5	14546	11.8 x 10 ⁻⁶	4.544	7767	0.486	0.058	959	9818	22.2
100	25	76.0	14546	11.6 x 10 ⁻⁶	4.544	7614	0.487	0.059	964	9619	22.6
49.0	15	189.9	7224	2.79 x 10 ⁻⁶	2.257	1828	0.530	0.042	759	2234	48.4
49.0	15	189.9	7223	2.79 x 10 ⁻⁶	2.257	1828	0.530	0.042	759	2234	48.4
75.0	25	129.9	10960	6.80 x 10 ⁻⁶	3.424	4455	0.503	0.050	851	5555	29.5
76.0	25	132.5	11103	6.66 x 10 ⁻⁶	3.469	4367	0.504	0.051	868	5443	30.5
59.9	20	172.4	8789	4.10 x 10 ⁻⁶	2.746	2685	0.518	0.046	806	3309	39.7
59.7	20	176.0	8759	4.01 x 10 ⁻⁶	2.736	2630	0.519	0.046	809	3240	40.4
40.2	15	289.6	5953	1.83 x 10 ⁻⁶	1.860	1199	0.543	0.040	734	1451	61.4
40.2	15	289.6	5953	1.83 x 10 ⁻⁶	1.860	1199	0.543	0.040	734	1451	61.4
125	30	56.2	18101	18.8 x 10 ⁻⁶	5.655	12355	0.472	0.066	1055	15806	17.1
125	30	57.0	18102	18.6 x 10 ⁻⁶	5.655	12182	0.473	0.066	1059	15579	17.4
125	25	47.4	18120	18.6 x 10 ⁻⁶	5.661	12208	0.473	0.066	1059	15612	17.4
125	25	45.8	18115	19.3 x 10 ⁻⁶	5.659	12634	0.472	0.066	1050	16172	16.8
205	100	70.9	29261	49.8 x 10 ⁻⁶	9.141	32646	0.443	0.091	1375	42907	10.2
205	100	69.5	29240	50.8 x 10 ⁻⁶	9.135	33303	0.442	0.091	1369	43797	10.0
173	75	72.1	24844	36.7 x 10 ⁻⁶	7.761	24077	0.452	0.081	1241	31369	11.9
175	75	72.6	25133	36.5 x 10 ⁻⁶	7.852	23911	0.452	0.082	1258	31146	12.1
152	50	65.0	21922	27.2 x 10 ⁻⁶	6.848	17805	0.461	0.075	1171	23002	14.3
153	50	64.3	22061	27.5 x 10 ⁻⁶	6.892	17998	0.461	0.075	1175	23260	14.2
124	75	149.7	17959	17.7 x 10 ⁻⁶	5.611	11596	0.474	0.066	1064	14810	18.1
124	90	183.4	17959	17.3 x 10 ⁻⁶	5.610	11358	0.475	0.067	1069	14499	18.5
99.0	40	120.7	14385	11.7 x 10 ⁻⁶	4.494	7671	0.487	0.058	952	9693	22.2
99.0	40	125.4	14386	11.3 x 10 ⁻⁶	4.494	7383	0.488	0.058	962	9321	23.1
75.0	30	159.3	10943	6.65 x 10 ⁻⁶	3.419	4359	0.504	0.050	856	5432	30.1
75.0	30	164.2	10942	6.45 x 10 ⁻⁶	3.418	4229	0.505	0.051	864	5267	31.1
100	50	153.5	14521	11.5 x 10 ⁻⁶	4.537	7539	0.487	0.059	965	9523	22.8
100	50	153.0	14519	11.5 x 10 ⁻⁶	4.536	7564	0.487	0.059	964	9555	22.7

1% CMC IN TAP WATER AT 75°F

TUBE 3

P (psig)	ΔV (cc)	t (sec)	ΔP ₁ (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ _a (centipoise)
500	60	12.38	67104	171 × 10 ⁻⁶	16.726	112177	0.406	0.149	2078	153242	5.23
496	170	36.37	66879	165 × 10 ⁻⁶	16.670	108188	0.407	0.149	2080	147614	5.41
405	200	60.50	56144	117 × 10 ⁻⁶	13.994	76515	0.417	0.128	1827	103222	6.49
310	200	95.82	43888	73.7 × 10 ⁻⁶	10.939	48311	0.431	0.105	1533	64243	8.15
250	80	57.08	35764	49.5 × 10 ⁻⁶	8.914	32440	0.443	0.089	1343	42628	10.0
208	90	92.22	29933	34.5 × 10 ⁻⁶	7.461	22589	0.454	0.079	1210	29377	12.2
170.6	90	142.11	24665	22.4 × 10 ⁻⁶	6.148	14659	0.467	0.070	1100	18838	15.6
152.2	40	82.15	22048	17.2 × 10 ⁻⁶	5.496	11270	0.475	0.065	1050	14383	18.3
152	40	80.35	22016	17.6 × 10 ⁻⁶	5.487	11523	0.474	0.065	1042	14714	17.9
104.2	40	180.18	15175	7.84 × 10 ⁻⁶	3.782	5138	0.499	0.053	900	6429	28.3
104	40	182.02	15145	7.76 × 10 ⁻⁶	3.775	5086	0.499	0.053	901	6363	28.4
103.9	40	181.35	15129	7.79 × 10 ⁻⁶	3.771	5105	0.499	0.053	899	6387	28.3
77.4	45	371.03	11319	4.28 × 10 ⁻⁶	2.821	2807	0.517	0.047	816	3463	39.0
50.0	20	386.28	7374	1.83 × 10 ⁻⁶	1.838	1198	0.543	0.039	726	1451	60.7
50.0	8	153.39	7374	1.84 × 10 ⁻⁶	1.838	1207	0.542	0.039	724	1462	60.2
125.3	80	240.11	18192	11.8 × 10 ⁻⁶	4.534	7712	0.487	0.058	959	9746	22.3
125	40	121.96	18148	11.6 × 10 ⁻⁶	4.523	7591	0.487	0.058	961	9590	22.6
160	60	107.90	23141	19.6 × 10 ⁻⁶	5.768	12871	0.471	0.067	1065	16483	16.8
159.5	120	218.92	23067	19.4 × 10 ⁻⁶	5.750	12687	0.472	0.067	1066	16242	17.0

TUBE 6

0.0	5	810.20	212	0.22 × 10 ⁻⁶	0.111	16	0.673	0.017	417	18	297
176	300	15.08	23080	703 × 10 ⁻⁶	12.012	51188	0.429	0.114	1668	68189	8.43
141	200	14.27	19271	495 × 10 ⁻⁶	10.030	36062	0.440	0.099	1481	47535	10.1
105	300	36.89	14889	287 × 10 ⁻⁶	7.749	20925	0.456	0.083	1277	27154	13.7
77.5	150	34.71	11217	153 × 10 ⁻⁶	5.838	11119	0.476	0.070	1119	14186	19.7
49.7	90	48.30	7304	65.8 × 10 ⁻⁶	3.802	4794	0.501	0.054	924	5989	30.4
35.9	80	78.89	5329	35.8 × 10 ⁻⁶	2.774	2609	0.519	0.047	822	3213	41.3
20.0	45	131.98	3044	12.0 × 10 ⁻⁶	1.584	877	0.552	0.038	709	1055	71.9
10.6	20	166.60	1690	4.24 × 10 ⁻⁶	0.879	309	0.584	0.031	624	364	116
10.7	20	160.12	1703	4.41 × 10 ⁻⁶	0.886	321	0.582	0.031	617	379	112
10.7	20	166.13	1702	4.25 × 10 ⁻⁶	0.886	310	0.583	0.031	628	365	116
5.6	20	394.91	967	1.79 × 10 ⁻⁶	0.503	130	0.610	0.026	550	151	159
5.8	8	155.31	996	1.82 × 10 ⁻⁶	0.518	133	0.610	0.026	561	154	161
15.5	20	91.82	2392	7.69 × 10 ⁻⁶	1.245	560	0.566	0.035	673	668	89
15.6	35	157.06	2405	7.87 × 10 ⁻⁶	1.252	573	0.565	0.035	670	684	88

1.5% CMC IN TAP WATER

SAMPLE 12 AT 100°F

TUBE 2

P (psig)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
401	200	50.74	54536	139×10^{-6}	17.037	91233	0.396	0.185	2524	126030	6.47
599	300	39.80	74055	266×10^{-6}	23.135	174467	0.387	0.216	2893	243497	4.55
504	200	34.28	65323	206×10^{-6}	20.407	135040	0.391	0.202	2725	187700	5.21
301	200	98.33	42591	71.8×10^{-6}	13.306	47078	0.405	0.171	2370	64379	9.90
250	175	117.41	35658	52.6×10^{-6}	11.140	34499	0.409	0.155	2173	46959	11.4
210	80	81.80	30169	34.5×10^{-6}	9.425	22637	0.415	0.147	2088	30622	14.7
152.5	40	86.72	22049	16.3×10^{-6}	6.888	10676	0.425	0.134	1937	14289	23.1
103.2	40	211.67	14987	6.67×10^{-6}	4.682	4374	0.437	0.120	1783	5783	38.8
103.0	20	110.71	14958	6.38×10^{-6}	4.673	4181	0.438	0.122	1808	5525	40.5
75.3	9	106.29	10974	2.99×10^{-6}	3.428	1960	0.448	0.115	1747	2564	64.0
50.8	9	235.02	7447	1.35×10^{-6}	2.326	886	0.458	0.104	1608	1148	97.0
122.0	20	75.57	17684	9.35×10^{-6}	5.525	6126	0.432	0.127	1872	8136	32.5
177.0	40	61.47	25526	23.0×10^{-6}	7.975	15062	0.420	0.140	2007	20256	18.9
151.5	20	45.48	21903	15.5×10^{-6}	6.843	10179	0.426	0.135	1955	13614	24.1
163.7	40	85.47	23654	16.5×10^{-6}	7.390	10832	0.425	0.143	2069	14501	24.4
138.2	20	57.67	20002	12.3×10^{-6}	6.249	8027	0.429	0.132	1932	10701	28.0

TUBE 5

198.8	400	14.63	23257	966×10^{-6}	14.520	68748	0.400	0.169	2324	94554	7.35
152.0	200	11.05	19618	639×10^{-6}	12.523	45510	0.405	0.162	2253	62203	9.64
97.6	300	42.90	13840	247×10^{-6}	8.999	17584	0.418	0.151	2156	23700	18.2
76.1	150	37.56	10981	141×10^{-6}	7.161	10042	0.426	0.142	2055	13428	25.5
50.2	80	48.75	7346	58.0×10^{-6}	4.797	4126	0.438	0.125	1865	5451	42.1
37.5	40	46.28	5529	30.5×10^{-6}	3.612	2173	0.446	0.117	1772	2847	60.8
25.1	50	133.91	3747	13.2×10^{-6}	2.448	939	0.458	0.107	1654	1217	96.3
25.1	40	109.78	3745	12.9×10^{-6}	2.447	916	0.458	0.108	1670	1187	98.7
17.2	20	113.87	2607	6.20×10^{-6}	1.704	442	0.468	0.099	1561	567	144
10.4	20	293.98	1627	2.40×10^{-6}	1.063	171	0.481	0.090	1460	217	234
10.2	9	140.15	1598	2.27×10^{-6}	1.044	161	0.481	0.090	1471	205	244
18.4	20	102.88	2778	6.87×10^{-6}	1.815	489	0.466	0.101	1595	629	138
31.4	40	70.62	4647	20.0×10^{-6}	3.036	1424	0.452	0.114	1746	1856	78.3

1.5% CMC IN TAP WATER

SAMPLE 19 AT 77°F

TUBE 2

P (psig)	AV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	v_a (centipoise)
504	200	41.81	67748	169 x 10 ⁻⁶	21.165	110720	0.344	0.390	4771	163535	6.20
398	150	47.93	55326	111 x 10 ⁻⁶	17.284	72437	0.362	0.300	3812	104313	7.93
303	70	40.60	43126	60.9 x 10 ⁻⁶	13.473	39907	0.388	0.221	2958	55632	11.6
203	80	112.72	29261	25.1 x 10 ⁻⁶	9.141	16427	0.427	0.145	2111	21945	19.9
151.0	40	113.19	21853	12.5 x 10 ⁻⁶	6.827	8179	0.457	0.111	1722	10609	30.8
103.0	20	133.45	14962	5.29 x 10 ⁻⁶	4.674	3469	0.494	0.083	1391	4356	51.4
50.9	20	533.46	7464	1.32 x 10 ⁻⁶	2.332	868	0.554	0.055	1038	1042	107
76.8	20	250.66	11192	2.82 x 10 ⁻⁶	3.496	1847	0.522	0.069	1225	2270	73.7
176.0	80	158.11	25420	17.9 x 10 ⁻⁶	7.941	11711	0.441	0.127	1904	15417	24.7
126.0	40	170.60	18262	8.28 x 10 ⁻⁶	5.705	5427	0.475	0.096	1545	6928	39.4

TUBE 8

23.5	350	42.40	3501	292 x 10 ⁻⁶	4.317	3126	0.499	0.078	1317	3912	52.8
18.5	300	55.63	2811	190 x 10 ⁻⁶	3.466	2042	0.517	0.067	1180	2519	65.9
0.0	8	136.83	174	2.06 x 10 ⁻⁶	0.214	22	0.714	0.023	620	24	421
0.0	20	353.86	173	2.00 x 10 ⁻⁶	0.213	21	0.715	0.024	632	24	434
11.7	150	68.85	1850	76.9 x 10 ⁻⁶	2.281	825	0.557	0.054	1034	989	110
5.9	80	104.88	1015	26.9 x 10 ⁻⁶	1.251	289	0.602	0.041	864	337	178
2.7	40	128.48	553	11.0 x 10 ⁻⁶	0.681	118	0.641	0.032	727	134	243
9.5	80	50.17	1527	56.3 x 10 ⁻⁶	1.883	604	0.570	0.049	958	718	126
15.3	150	40.32	2375	131 x 10 ⁻⁶	2.928	1409	0.533	0.061	1111	1717	81.6

1.5% CMC IN TAP WATER

SAMPLE 19 AT 100°F

TUBE 3

P (psig)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)^w$ (sec ⁻¹)	μ_a (centipoise)
497	250	63.28	68394	140×10^{-6}	17.044	91497	0.388	0.204	2728	127647	6.39
402	150	54.90	56480	96.5×10^{-6}	14.075	63278	0.400	0.170	2330	87039	7.74
601	400	70.21	79686	201×10^{-6}	19.858	131946	0.375	0.237	3100	186809	5.09
308	125	78.29	43995	56.4×10^{-6}	10.964	36978	0.417	0.136	1938	49882	10.5
252	80	75.68	36239	37.3×10^{-6}	9.031	24482	0.431	0.116	1700	32564	13.3
200	80	128.30	28907	22.0×10^{-6}	7.204	14441	0.448	0.098	1495	18883	18.3
162.0	40	102.40	23484	13.8×10^{-6}	5.852	9047	0.464	0.086	1344	11662	24.0
182.5	80	155.42	26410	18.2×10^{-6}	6.581	11921	0.455	0.092	1421	15496	20.3
142.0	45	152.54	20614	10.4×10^{-6}	5.137	6832	0.473	0.079	1262	8736	28.2
121.7	20	97.55	17700	7.24×10^{-6}	4.411	4748	0.485	0.073	1193	6009	35.2
104.0	20	135.48	15155	5.21×10^{-6}	3.777	3419	0.496	0.067	1122	4288	42.2
104.0	8	51.96	15154	5.44×10^{-6}	3.776	3566	0.494	0.066	1108	4478	40.4
84.0	20	221.19	12277	3.19×10^{-6}	3.059	2094	0.512	0.061	1059	2593	56.5
84.2	9	91.82	12305	3.46×10^{-6}	3.066	2270	0.509	0.060	1034	2817	52.1
59.9	8	166.30	8807	1.70×10^{-6}	2.195	1114	0.533	0.052	947	1358	77.4
49.8	9	276.40	7352	1.15×10^{-6}	1.832	754	0.546	0.049	918	911	96.3
49.8	20	577.45	7352	1.22×10^{-6}	1.832	802	0.544	0.048	896	971	90.4
41.0	8	335.55	6084	0.84×10^{-6}	1.516	552	0.556	0.045	862	662	109.6
72.1	23	320.60	10561	2.48×10^{-6}	2.632	1625	0.520	0.056	992	2000	63.0
72.1	9	124.80	10561	2.55×10^{-6}	2.632	1670	0.519	0.056	983	2057	61.3
93.0	20	168.65	13568	4.19×10^{-6}	3.381	2746	0.503	0.063	1073	3425	47.3
112.0	40	218.00	16298	6.48×10^{-6}	4.062	4250	0.489	0.068	1133	5361	36.3
132.2	80	305.65	19198	9.24×10^{-6}	4.784	6062	0.477	0.075	1212	7724	29.7
152.2	40	113.29	22063	12.5×10^{-6}	5.498	8177	0.467	0.082	1293	10510	25.1
152.3	80	224.58	22075	12.6×10^{-6}	5.501	8250	0.467	0.082	1291	10606	24.8
172.0	80	176.53	24892	16.0×10^{-6}	6.203	10496	0.459	0.089	1377	13590	21.9
190.8	40	72.39	27576	19.5×10^{-6}	6.872	12797	0.452	0.095	1462	16671	19.7
190.5	70	127.00	27531	19.5×10^{-6}	6.861	12765	0.452	0.095	1460	16628	19.8
103.0	40	278.16	14991	5.08×10^{-6}	3.736	3330	0.497	0.066	1118	4174	42.9

1.5% CMC IN TAP WATER

SAMPLE 19 AT 100°F

TUBE 6

P (psig)	ΔV (cc)	t (sec)	ΔP ₁ (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ _a (centipoise)
0.0	5	1191.05	228	0.15 × 10 ⁻⁶	0.118	11	0.686	0.023	577	12	471
5.5	15	386.71	1019	1.37 × 10 ⁻⁶	0.530	100	0.613	0.032	676	116	220
5.3	8	226.03	990	1.25 × 10 ⁻⁶	0.515	91	0.616	0.032	689	105	234
10.8	20	204.83	1781	3.45 × 10 ⁻⁶	0.927	251	0.582	0.037	745	296	150
10.6	8	84.41	1752	3.35 × 10 ⁻⁶	0.912	243	0.583	0.037	743	287	152
20.4	19	70.49	3162	9.52 × 10 ⁻⁶	1.646	694	0.549	0.045	851	836	94.3
30.4	45	82.67	4600	19.2 × 10 ⁻⁶	2.394	1401	0.526	0.053	949	1717	66.8
40.3	90	98.13	6020	32.4 × 10 ⁻⁶	3.133	2360	0.508	0.060	1041	2930	51.2
60.1	40	20.40	8850	69.2 × 10 ⁻⁶	4.606	5045	0.483	0.075	1223	6394	34.5
83.5	80	22.00	12159	128 × 10 ⁻⁶	6.328	9356	0.463	0.092	1440	12071	25.1
105.0	220	36.71	15108	212 × 10 ⁻⁶	7.863	15420	0.446	0.106	1608	20202	18.6
144.0	425	36.67	20099	409 × 10 ⁻⁶	10.461	29821	0.425	0.132	1907	39925	12.6
181.5	400	22.31	24318	633 × 10 ⁻⁶	12.656	46132	0.410	0.155	2171	62718	9.66
72.0	80	29.00	10498	97.4 × 10 ⁻⁶	5.464	7098	0.472	0.083	1328	9083	28.8
49.7	90	66.38	7320	47.9 × 10 ⁻⁶	3.810	3489	0.495	0.067	1122	4377	41.7
35.1	40	57.41	5224	24.6 × 10 ⁻⁶	2.719	1793	0.517	0.056	989	2211	58.9
45.6	80	68.33	6728	41.4 × 10 ⁻⁶	3.502	3012	0.500	0.064	1078	3765	44.5
25.3	40	105.00	3811	13.5 × 10 ⁻⁶	1.983	980	0.537	0.049	896	1191	79.7
15.3	20	122.81	2371	5.75 × 10 ⁻⁶	1.234	419	0.565	0.041	787	500	118
60.0	80	40.92	8782	69.0 × 10 ⁻⁶	4.571	5030	0.483	0.074	1214	6375	34.3
49.3	40	31.37	7253	45.0 × 10 ⁻⁶	3.775	3281	0.497	0.067	1132	4109	44.0
40.3	90	105.12	5960	30.2 × 10 ⁻⁶	3.102	2203	0.511	0.061	1054	2731	54.4
30.7	40	78.09	4578	18.1 × 10 ⁻⁶	2.383	1318	0.528	0.054	965	1613	70.7
20.7	20	77.37	3139	9.13 × 10 ⁻⁶	1.634	665	0.550	0.046	859	801	97.6
15.3	20	129.25	2361	5.46 × 10 ⁻⁶	1.229	398	0.567	0.041	802	474	124

1.5% CMC IN TAP WATER

SAMPLE 19 AT 125°F

TUBE 2

P (psig)	AV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	$\frac{Q}{t}$ (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
494	300	40.31	59275	263 x 10 ⁻⁶	18,518	172259	0.367	0.221	2842	246486	3.60
403	200	39.53	52644	179 x 10 ⁻⁶	16,446	117106	0.383	0.187	2489	164192	4.80
300	150	50.22	41436	105 x 10 ⁻⁶	12,945	69134	0.406	0.141	1962	94468	6.56
208	100	71.08	29694	49.7 x 10 ⁻⁶	9,276	32563	0.437	0.099	1466	43043	10.3
152.0	50	71.61	21952	24.7 x 10 ⁻⁶	6,858	16161	0.467	0.075	1177	20779	15.8

TUBE 5

100.0	150	13.10	13401	404 x 10 ⁻⁶	8,758	28775	0.442	0.093	1401	37842	11.1
61.0	150	33.13	8753	160 x 10 ⁻⁶	5,721	11378	0.481	0.064	1039	14442	19.0
40.6	80	37.37	5951	75.6 x 10 ⁻⁶	3,890	5380	0.513	0.047	825	6657	28.0
30.3	50	40.77	4493	43.3 x 10 ⁻⁶	2,936	3082	0.536	0.040	721	3748	37.5
15.2	35	94.54	2329	13.1 x 10 ⁻⁶	1,522	930	0.587	0.030	559	1094	66.6
7.2	20	183.34	1177	3.85 x 10 ⁻⁶	0,769	274	0.638	0.021	483	313	118

TUBE 8

15.0	70	9.29	2237	266 x 10 ⁻⁶	2,759	2853	0.540	0.038	693	3462	38.2
0.0	20	220.40	136	3.20 x 10 ⁻⁶	0.168	34	0.725	0.013	347	38	213
0.0	15	173.73	135	3.05 x 10 ⁻⁶	0.167	33	0.727	0.013	359	36	223
5.2	40	27.13	891	52.1 x 10 ⁻⁶	1.086	558	0.608	0.023	492	642	80.2
10.2	80	20.47	1585	138 x 10 ⁻⁶	1,954	1480	0.567	0.031	606	1762	53.1
3.2	30	37.83	590	28.0 x 10 ⁻⁶	0.727	300	0.634	0.020	437	344	101
7.4	55	24.84	1188	78.2 x 10 ⁻⁶	1,465	838	0.591	0.027	561	984	71.3

1.5% CMC IN TAP WATER

SAMPLE 19 AT 143°F

TUBE 8

20.0	200	12.32	2750	573 x 10 ⁻⁶	3,391	6148	0.568	0.024	465	7315	22.2
10.3	165	25.78	1586	226 x 10 ⁻⁶	1,955	2424	0.592	0.019	398	2842	32.9
5.0	70	30.60	856	80.8 x 10 ⁻⁶	1,056	866	0.617	0.016	350	1001	50.5
0.0	20	142.82	140	4.95 x 10 ⁻⁶	0.173	53	0.687	0.011	281	59	140
0.0	40	285.60	136	4.95 x 10 ⁻⁶	0.167	53	0.687	0.011	273	59	136
2.1	90	112.31	435	28.3 x 10 ⁻⁶	0.537	303	0.644	0.014	309	346	74.4
0.0	40	285.63	131	4.95 x 10 ⁻⁶	0.162	53	0.687	0.011	264	59	131
6.9	120	37.16	1110	114 x 10 ⁻⁶	1,369	1223	0.609	0.018	384	1419	46.2
0.0	40	319.66	125	4.42 x 10 ⁻⁶	0.154	47	0.690	0.011	271	53	140

1.5% CMC IN TAP WATER

SAMPLE 23 AT 70°F

TUBE 8

P (psig)	AV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
23.2	150	35.90	3499	148×10^{-6}	4.315	1582	0.434	0.176	2601	2098	98.5
0.0	9	355.74	175	0.89×10^{-6}	0.216	10	0.754	0.039	1126	10	996
18.8	150	56.50	2871	93.8×10^{-6}	3.541	1005	0.463	0.145	2265	1297	131
0.2	8	234.91	198	1.20×10^{-6}	0.244	13	0.735	0.037	1028	14	831
2.2	20	182.01	485	3.88×10^{-6}	0.599	42	0.662	0.051	1202	47	611
3.9	40	189.76	729	7.44×10^{-6}	0.899	80	0.621	0.059	1289	92	468
10.1	80	97.48	1619	29.0×10^{-6}	1.997	311	0.536	0.092	1680	378	253
3.1	20	124.05	610	5.69×10^{-6}	0.753	61	0.638	0.055	1232	70	517
0.0	8	348.83	164	0.81×10^{-6}	0.202	9	0.760	0.039	1134	9	1031
5.1	40	137.97	897	10.2×10^{-6}	1.106	110	0.601	0.066	1370	128	414
7.6	90	172.17	1255	18.5×10^{-6}	1.547	198	0.564	0.078	1514	236	314
6.5	40	99.19	1094	14.2×10^{-6}	1.349	153	0.581	0.073	1457	180	358
13.6	80	57.01	2113	49.6×10^{-6}	2.605	531	0.502	0.111	1893	663	188
1.1	8	133.42	313	2.12×10^{-6}	0.386	23	0.700	0.043	1114	25	736
2.7	20	147.48	543	4.79×10^{-6}	0.670	51	0.649	0.052	1199	58	550
8.5	80	129.12	1376	21.9×10^{-6}	1.697	235	0.554	0.083	1564	282	288

SAMPLE 23 AT 122°F

TUBE 8

14.5	150	32.45	2242	163×10^{-6}	2.765	1751	0.558	0.043	818	2097	63.1
0.0	9	122.59	175	2.59×10^{-6}	0.216	28	0.681	0.022	552	31	332
10.9	150	51.01	1732	104×10^{-6}	2.136	1114	0.571	0.039	761	1322	77.3
1.9	20	64.42	442	11.0×10^{-6}	0.546	118	0.638	0.026	567	134	195
8.0	80	45.87	1316	61.6×10^{-6}	1.622	660	0.587	0.036	728	777	100
3.2	40	74.02	625	19.1×10^{-6}	0.771	205	0.622	0.028	615	236	157
6.6	80	61.64	1111	45.8×10^{-6}	1.371	491	0.596	0.034	705	575	114
4.3	40	53.32	779	26.5×10^{-6}	0.961	284	0.612	0.030	647	329	140
0.0	8	122.39	160	2.31×10^{-6}	0.197	25	0.685	0.022	545	28	342
1.3	20	97.02	347	7.28×10^{-6}	0.427	78	0.651	0.025	581	89	231

1.5% CMC IN TAP WATER

SAMPLE 23 AT 132°F

TUBE 8

P (psig)	AV (cc)	t (sec)	ΔP_1 (lb _F /ft ²)	Q (ft ³ /sec)	τ (lb _F /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _F /ft ²)	Y (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	ν_a (centipoise)
14.5	150	27.27	2202	194×10^{-6}	2.715	2083	0.572	0.034	675	2473	52.6
0.0	9	112.23	144	2.83×10^{-6}	0.178	30	0.716	0.015	409	33	255
5.2	80	71.65	890	39.4×10^{-6}	1.098	423	0.626	0.025	547	486	108
1.1	20	87.79	299	8.05×10^{-6}	0.369	86	0.681	0.018	438	96	183
3.1	40	64.92	586	21.8×10^{-6}	0.722	233	0.647	0.021	488	265	130
1.9	20	55.60	412	12.7×10^{-6}	0.508	136	0.665	0.019	462	153	159
4.1	40	46.73	727	30.2×10^{-6}	0.897	324	0.635	0.023	511	371	116
6.6	80	50.42	1083	56.0×10^{-6}	1.336	601	0.614	0.026	563	695	92.0
0.0	9	135.08	134	2.35×10^{-6}	0.166	25	0.723	0.016	432	28	287
8.6	80	34.58	1365	81.7×10^{-6}	1.684	876	0.601	0.029	598	1021	78.9
12.3	80	19.48	1883	145×10^{-6}	2.322	1555	0.582	0.032	647	1835	60.6
1.7	20	63.02	373	11.2×10^{-6}	0.459	120	0.669	0.019	448	135	163
3.3	40	62.97	602	22.4×10^{-6}	0.742	241	0.646	0.022	493	274	130
5.4	40	35.06	901	40.3×10^{-6}	1.112	432	0.626	0.025	548	497	107

SAMPLE 23 AT 145°F

TUBE 8

14.8	200	26.65	2226	265×10^{-6}	2.745	2842	0.593	0.025	504	3329	39.5
0.0	9	73.88	152	4.30×10^{-6}	0.187	46	0.725	0.012	315	51	178
10.7	150	34.51	1669	153×10^{-6}	2.058	1646	0.611	0.022	476	1908	51.7
0.0	20	182.85	146	3.86×10^{-6}	0.180	41	0.729	0.012	325	45	190
5.9	80	43.81	990	64.5×10^{-6}	1.221	692	0.639	0.019	424	789	74.1
3.0	40	47.57	573	29.7×10^{-6}	0.707	318	0.663	0.015	367	359	94.4
1.3	20	50.37	328	14.0×10^{-6}	0.405	150	0.687	0.013	322	167	116
2.2	40	67.37	456	21.0×10^{-6}	0.563	225	0.675	0.015	355	252	107
4.2	80	64.75	741	43.6×10^{-6}	0.914	468	0.651	0.017	387	531	82.5
1.2	15	43.31	309	12.2×10^{-6}	0.381	131	0.692	0.013	329	146	125
5.2	80	51.18	881	55.2×10^{-6}	1.086	592	0.644	0.018	407	674	77.1
0.0	8	78.20	133	3.61×10^{-6}	0.164	39	0.731	0.011	310	42	185
8.4	80	26.88	1331	105×10^{-6}	1.642	1127	0.623	0.021	450	1298	60.6
0.2	18	139.36	158	4.56×10^{-6}	0.195	49	0.723	0.012	315	54	174
1.1	40	134.93	287	10.5×10^{-6}	0.354	112	0.697	0.013	336	124	136
4.9	80	57.47	830	49.2×10^{-6}	1.023	527	0.647	0.018	407	599	81.8
2.1	20	39.59	427	17.8×10^{-6}	0.526	191	0.680	0.015	364	214	118

1.5% CMC IN TAP WATER

SAMPLE 24 AT 71°F

TUBE 5

P (psia)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	μ_a (centipoise)
151.3	300	32.61	21234	325×10^{-6}	13.877	23119	0.342	0.448	5453	34253	19.4
127.5	300	46.33	18171	229×10^{-6}	11.876	16272	0.356	0.376	4722	23634	24.1
102.2	200	55.11	14772	128×10^{-6}	9.654	9120	0.379	0.304	4000	12850	36.0
80.7	90	45.54	11753	69.8×10^{-6}	7.681	4966	0.404	0.247	3422	6799	54.1
61.2	90	86.62	8967	36.7×10^{-6}	5.860	2611	0.430	0.199	2912	3477	80.7
50.3	40	57.08	7400	24.8×10^{-6}	4.836	1761	0.446	0.173	2612	2308	100
40.6	40	91.37	6005	15.5×10^{-6}	3.924	1100	0.465	0.151	2380	1417	133
30.1	20	87.37	4493	8.07×10^{-6}	2.936	574	0.491	0.130	2154	723	195
20.2	8	75.25	3067	3.86×10^{-6}	2.005	274	0.521	0.108	1901	338	284
20.3	20	185.61	3081	3.81×10^{-6}	2.014	271	0.522	0.108	1919	333	290
15.8	8	117.38	2433	2.41×10^{-6}	1.590	171	0.540	0.099	1818	208	366
10.6	20	564.59	1683	1.25×10^{-6}	1.100	89	0.567	0.086	1681	106	497

SAMPLE 24 AT 71°F

TUBE 8

3.3	20	152.35	631	4.64×10^{-6}	0.778	49	0.590	0.078	1584	58	639
0.0	9	620.36	155	0.51×10^{-6}	0.192	5	0.679	0.060	1481	6	1495
1.5	20	354.11	371	1.99×10^{-6}	0.457	21	0.624	0.068	1481	25	890
5.1	40	163.51	868	8.33×10^{-6}	1.095	89	0.566	0.086	1670	106	493
6.9	80	214.93	1145	13.1×10^{-6}	1.412	141	0.548	0.094	1754	170	398
10.1	80	110.66	1603	25.5×10^{-6}	1.877	274	0.521	0.106	1876	337	281
12.0	80	82.72	1873	34.2×10^{-6}	2.310	366	0.509	0.114	1971	454	243
15.2	170	117.77	2328	51.0×10^{-6}	2.871	547	0.493	0.128	2139	687	200
21.7	300	100.89	3248	105×10^{-6}	4.006	1126	0.464	0.154	2415	1451	132

SAMPLE 24 AT 79°F

TUBE 8

10.0	80	86.99	1635	32.5×10^{-6}	2.016	348	0.522	0.095	1681	428	225
5.1	40	132.13	928	10.7×10^{-6}	1.144	115	0.574	0.075	1484	136	403
3.2	20	110.35	653	6.40×10^{-6}	0.805	69	0.598	0.064	1332	80	481
3.2	19	103.68	652	6.47×10^{-6}	0.804	69	0.598	0.064	1322	81	475
5.5	40	110.35	982	12.8×10^{-6}	1.211	137	0.566	0.075	1451	164	355
7.7	80	135.67	1297	20.8×10^{-6}	1.599	223	0.543	0.085	1569	270	283
13.5	80	49.75	2127	56.8×10^{-6}	2.622	609	0.496	0.109	1829	764	164
19.5	200	60.30	2977	117×10^{-6}	3.671	1256	0.462	0.136	2123	1622	108
17.0	80	32.68	2618	86.5×10^{-6}	3.228	927	0.476	0.125	2007	1182	131
2.1	40	348.41	476	4.05×10^{-6}	0.587	43	0.620	0.057	1231	50	561
1.3	20	260.72	360	2.71×10^{-6}	0.444	29	0.639	0.052	1166	33	641
0.0	9	402.97	172	0.79×10^{-6}	0.213	8	0.697	0.048	1224	9	1085
29.6	300	37.99	4362	279×10^{-6}	5.378	2990	0.421	0.184	2651	4017	64.1
24.5	200	39.09	3650	181×10^{-6}	4.513	1938	0.442	0.159	2389	2550	85.8
0.0	8	408.66	157	0.69×10^{-6}	0.193	7	0.703	0.047	1221	8	1130

1.5% CMC IN TAP WATER

SAMPLE 24 AT 85°F

TUBE 8

P (psig)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{320}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	ν_a (centipoise)
14.5	80	39.09	2239	72.3×10^{-6}	2.761	775	0.477	0.116	1867	988	134
1.1	20	295.84	312	2.39×10^{-6}	0.385	26	0.672	0.043	1053	29	641
19.7	150	38.62	2971	137×10^{-6}	3.663	1471	0.440	0.148	2211	1939	90.5
2.8	40	235.71	550	5.99×10^{-6}	0.679	64	0.619	0.051	1117	74	438
24.0	150	25.31	3562	209×10^{-6}	4.392	2244	0.416	0.178	2524	3033	69.3
1.7	18	202.08	385	3.15×10^{-6}	0.475	34	0.656	0.047	1106	38	597
4.9	40	116.02	845	12.2×10^{-6}	1.042	131	0.579	0.062	1239	154	323
10.7	80	68.69	1677	41.1×10^{-6}	2.068	441	0.509	0.093	1608	547	181
7.6	40	61.87	1230	22.8×10^{-6}	1.516	245	0.543	0.077	1417	296	245
0.7	10	221.48	236	1.59×10^{-6}	0.291	17	0.695	0.040	1025	19	733
0.9	8	150.08	264	1.88×10^{-6}	0.326	20	0.686	0.041	1033	23	693
6.7	40	76.00	1098	18.6×10^{-6}	1.354	199	0.555	0.072	1362	239	271
3.9	20	87.72	694	8.05×10^{-6}	0.856	86	0.602	0.058	1222	101	407
12.7	80	51.10	1957	55.3×10^{-6}	2.413	593	0.492	0.104	1736	746	155
5.3	40	108.77	892	13.0×10^{-6}	1.100	139	0.575	0.064	1273	165	319
3.2	20	116.81	588	6.05×10^{-6}	0.726	65	0.619	0.055	1189	75	464

SAMPLE 24 AT 87°F

TUBE 8

7.4	80	119.47	1258	23.7×10^{-6}	1.551	254	0.562	0.069	1332	303	245
5.0	40	106.74	911	13.2×10^{-6}	1.123	142	0.599	0.058	1200	166	325
2.3	20	121.22	521	5.83×10^{-6}	0.642	62	0.651	0.043	1008	71	434
10.8	80	63.29	1742	44.6×10^{-6}	2.147	479	0.521	0.086	1524	589	175
18.8	150	39.78	2876	133×10^{-6}	3.546	1428	0.451	0.134	2047	1862	91.2
24.5	300	46.11	3658	230×10^{-6}	4.510	2464	0.416	0.175	2488	3328	64.9
5.2	50	122.63	918	14.4×10^{-6}	1.133	154	0.594	0.057	1170	181	300
2.4	20	122.31	514	5.77×10^{-6}	0.634	62	0.652	0.043	999	70	433
14.3	150	72.01	2220	73.6×10^{-6}	2.737	789	0.489	0.105	1735	995	132
30.4	400	39.85	4425	354×10^{-6}	5.456	3801	0.388	0.222	2982	5298	49.3
7.2	40	62.73	1185	22.5×10^{-6}	1.461	241	0.565	0.066	1276	288	243
4.0	20	70.67	723	9.99×10^{-6}	0.892	107	0.617	0.050	1077	124	345
10.9	80	62.38	1714	45.3×10^{-6}	2.113	486	0.520	0.085	1494	598	169
35.7	400	29.41	5079	480×10^{-6}	6.263	5151	0.369	0.268	3450	7354	40.8
22.0	150	31.44	3270	168×10^{-6}	4.033	1807	0.436	0.153	2272	2391	80.8

1.5% CMC IN TAP WATER
ISHIHARA SAMPLE 1 AT 86°F

TUBE 5

P (psig)	ΔV (cc)	t (sec)	ΔP_1 (lb _f /ft ²)	Q (ft ³ /sec)	τ (lb _f /ft ²)	$\frac{32Q}{\pi D^3}$ (sec ⁻¹)	n'	k' (lb _f /ft ²)	γ (centipoise)	$\left(\frac{dv}{dr}\right)_w$ (sec ⁻¹)	ν_a (centipoise)
101.0	100	19.90	14465	177 x 10 ⁻⁶	9.454	12628	0.407	0.203	2832	17235	26.3
75.2	50	19.32	10910	91.4 x 10 ⁻⁶	7.130	6504	0.427	0.167	2436	8683	39.3
59.5	50	33.72	8687	52.4 x 10 ⁻⁶	5.677	3726	0.445	0.147	2211	4890	55.6
50.2	30	28.67	7355	37.0 x 10 ⁻⁶	4.807	2630	0.456	0.133	2053	3415	67.4
40.1	30	46.11	5906	23.0 x 10 ⁻⁶	3.860	1635	0.470	0.119	1891	2095	88.2
29.6	30	85.41	4395	12.4 x 10 ⁻⁶	2.873	883	0.490	0.104	1718	1113	124
19.8	20	124.61	2984	5.67 x 10 ⁻⁶	1.950	403	0.514	0.089	1555	499	187
15.4	8	78.40	2350	3.60 x 10 ⁻⁶	1.536	256	0.528	0.082	1472	314	234
10.3	8	179.29	1615	1.58 x 10 ⁻⁶	1.056	112	0.554	0.077	1463	135	375
5.5	9	439.99	924	0.72 x 10 ⁻⁶	0.604	51	0.578	0.062	1232	61	476
142.3	150	14.56	19686	364 x 10 ⁻⁶	12.866	25889	0.384	0.259	3450	36263	17

ISHIHARA SAMPLE 8 AT 86°F

TUBE 5

50.3	50	49.73	7376	35.5 x 10 ⁻⁶	4.820	2527	0.468	0.123	1949	3244	71.2
40.5	40	62.70	5969	22.5 x 10 ⁻⁶	3.901	1603	0.484	0.110	1799	2031	92.0
30.3	30	84.77	4501	12.5 x 10 ⁻⁶	2.942	889	0.503	0.096	1642	1109	127
25.5	20	77.93	3809	9.06 x 10 ⁻⁶	2.490	645	0.514	0.089	1558	797	150
20.3	30	175.54	3060	6.04 x 10 ⁻⁶	2.000	429	0.528	0.081	1461	525	182
14.8	20	211.69	2267	3.34 x 10 ⁻⁶	1.482	237	0.548	0.074	1383	286	248
10.5	9	167.17	1648	1.90 x 10 ⁻⁶	1.077	135	0.567	0.067	1296	161	320
5.4	9	449.01	913	0.71 x 10 ⁻⁶	0.597	50	0.600	0.057	1183	59	486
32.2	40	82.22	5201	17.8 x 10 ⁻⁶	3.399	1223	0.493	0.102	1707	1537	106
45.5	50	64.15	6680	27.5 x 10 ⁻⁶	4.366	1959	0.477	0.118	1897	2496	83.7
54.9	50	42.28	8024	41.8 x 10 ⁻⁶	5.244	2972	0.463	0.130	2030	3835	65.5
76.3	50	21.10	11067	83.7 x 10 ⁻⁶	7.233	5955	0.439	0.159	2370	7855	44.1

APPENDIX C

COMPUTER PROGRAM LIST

DONALD DAVID RANDOLPH

FORTRAN SOURCE LIST

ISN SOURCE STATEMENT

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0 $IBFTC DKNAME NODECK
C   CAPILLARY VISCOMETER FOR NON-NEWTONIAN LIQUIDS
1   DIMENSION DELP1(100),V(3,100),T(100),Q(100),DELPT(100),XXX(100),YY
    1Y(100),X(100),Y(100),TITLE(2,13),GB(1000),IDT(100),IV(3,100),DELPH
    2(100),LC(100),YY(3),XX(3),XITLE(5),TOTY(100),TOTX(100)
2   EQUIVALENCE (GB(1),DELP1(1)), (GB(101),V(1)), (GB(401),T(1)),
    1 (GB(501),Q(1)),(GB(601),DELPT(1)),(GB(701),XXX(1)),(GB(801),YYY(
    21)),(GB(901),DELPH(1))
3   REAL L,K1,K2
4   DO 2 I=1,1000
5   2 GB(I)=0.0
7   READ(5,100) ((TITLE(I,J),J=1,13),I=1,2),NUM,PGEL,L,D,K2,IFGX,JFOX,
    1 (LC(I),DELP1(I)),(V(J,I),J=1,2),T(I),I=1,NUM)
33  100 FORMAT (13A6/13A6/12,2F10.5,2E14.8,2I5/(12,3F10.2,10X,F10.2,28X))
34  DO 3 I=1,5
35  3 XITLE(I)=TITLE(1,I)
37  IF(NUM.GT.99) GO TO 300
42  DO 10 I=1,NUM
43  V(3,I) = V(1,I)-V(2,I)
44  DELP2 = DELP1(I)*144.0
45  DELPH(I) = (PGEL*(147.0*L*30.48+V(1,I)+V(2,I)))/(30.48*147.0)
46  Q(I)=(V(3,I)/T(I))*35.314E-06
47  IF(JFOX.EQ.0) GO TO 5
52  DELPT(I)=DELP2+DELPH(I)
53  YYY(I)=DELPT(I)/Q(I)
54  GO TO 6
55  5 DELPT(I) = DELP2+DELPH(I)-Q(I)*Q(I)*K2
56  YYY(I) = D*DELPT(I)/(4.0*L)
57  XXX(I) = (32.0/(3.1415927*D*D*D))*Q(I)
60  Y(I) = ALOG(YYY(I))
61  X(I) = ALOG(XXX(I))
62  6 IDT(I)=DELPT(I)+0.5
63  DO 9 J=1,3
64  9 IV(J,I)=V(J,I)+0.5
66  10 CONTINUE
70  DO 55 I=1,NUM
71  WRITE(7,7)YYY(I),XXX(I)
72  7 FORMAT(F10.5,F10.2)
73  55 CONTINUE
75  DO 56 I=1,NUM
76  WRITE(7,8)X(I),Y(I)
77  8 FORMAT(2E12.6)
100  56 CONTINUE
102  IF(JFOX.GT.0) GO TO 20
105  WRITE (6,200) ((TITLE(I,J),J=1,13),I=1,2),PGEL,L,D,K2
116  200 FORMAT(1H1,10X,13A6/10X,13A6///16X,5HP = ,F6.2,8X,5HL = ,F6.3,
    1 8X,5HD = ,1PE10.4,8X,6HK2 = ,0PE10.4// 2X,5HPOINT,1X,5HDELTA,
    2 28X,5HDELTA,3X,5HDELTA/ 3X,3HND.,3X,4HP(1),2X,4HV(1),2X,4HV(2),
    3 2X,4HV(3),5X,1HT,5X,4HP(H),4X,4HP(T),8X,1HQ,8X,3H(Y),5X,7HNLOG(Y)
    4 ,6X,3H(X),6X,7HNLOG(X))
117  MUM=NUM
120  DO 60 K = 1,MUM
121  WRITE(6,401) LC(K),DELP1(K),((IV(L1,K),L1=1,3),T(K),DELPH(K),IDT(K)
    1,Q(K),YYY(K),Y(K),XXX(K),X(K)
126  401 FORMAT(2X,15,F6.1,3I6,F8.2,F7.1,18,F13.8,F8.3,F11.5,F11.3,F11.5)

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ISN	SOURCE STATEMENT
127	60 CONTINUE
131	GO TO 1
132	20 WRITE(6,210) ((TITLE(I,J),J=1,13),I=1,2),PGEL,L,D
143	210 FORMAT(1H1,10X,13A6/10X,13A6///16X,5HP = ,F6.2, 8X,5HL = ,F6.2, 1 3X,6HMU = ,1PF10.4 // 2X,5HPDINT,3X,5HDELTA, 2 3BX,5HDELTA,3X,5HDELTA/3X,3HNO.,4X,4HP(1),4X,4HV(1),3X,4HV(2), 3 3X,4HV(3),7X,1HT,10X,4HP(H),4X,4HP(T),8X,1HQ,10X,3H(Y)/)
144	405 N1=1
145	MUM=NUM
146	IF(MUM.GT.48) MUM=48
151	406 WRITE(6,407) (LC(K),DELP1(K), (IV(L1,K),L1=1,3),T(K),DELPH(K),IDT(K 1),Q(K),YYY(K), K=N1,MUM)
162	407 FORMAT(2X,I5,OPF8.2,3I7,F10.3,F12.4,I8,F11.7,F12.1)
163	IF(MUM.GE.NUM) GO TO 30
166	500 FORMAT(1H1)
167	WRITE(6,500)
170	N1=MUM+1
171	MUM=NUM
172	GO TO 406
173	30 SX2=0.
174	SXY=0.
175	SX=0.
176	SY=0.
177	ZUM=NUM
200	I1=1
201	I2=NUM
202	40 DO 50 I=I1,I2
203	XXX(I)=Q(I)
204	IF(YYY(I).GE.0.0.AND. XXX(I).GE.0.0) GO TO 49
207	NUM=NUM-1
210	IF(I-I2) 52,51,52
211	49 SXY=SXY+YYY(I)*XXX(I)
212	SX=SX+XXX(I)
213	SY=SY+YYY(I)
214	50 SX2=SX2+XXX(I)*XXX(I)
216	51 K2= (SXY-(SX*SY)/ZUM)/(SX2-(SX*SX)/ZUM)
217	IF(K2.LT.0.) GO TO 70
222	K1= SY/ZUM- (K2*(SX/ZUM))
223	IF(K1.LT.0.) GO TO 70
226	R=((8.0*D*L)/(22./7.*K1)*2.09E-05)**0.25
227	WRITE(6,230) K1,R,SX,SXY,K2,SX2,SY
230	230 FORMAT(1H0/ 5X,5HK1 = , E14.8, 7X,4HR = , E14.8,9X,9HSUM X = , 1 E14.8, 9X,9HSUM XY = , E14.8/ 5X,5HK2 = ,E14.8,34X,9HSUM X2 = 2 ,E14.8, 9X,9HSUM Y = , E14.8)
231	GO TO 1
232	52 ZUM=ZUM-1.0
233	I2=I2-1
234	I1=I1+1
235	DO 53 J=I,I2
236	YYY(J)=YYY(J+1)
237	53 Q(J)=Q(J+1)
241	GO TO 40
242	70 WRITE(6,71) K1,K2
243	71 FORMAT(1H1,5X,5HK1 = , E14.6, 5X,5HK2 = , E14.6/ 41H0 THIS CASE C 1ANNOT BE COMPLETED BECAUSE / 10X,39HONE OF THE ABOVE VALUES BEING

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      2 NEGATIVE. )  
244      GO TO 1  
245      300 WRITE(6,301)  
246      301 FORMAT(41H1 THIS CASE CANNOT BE PROCESSED BECAUSE / 2TH OF TO  
      10 MANY DATA POINTS.)  
247      GO TO 1  
250      702 STOP  
251      END
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$JOB  WATFOR      DONALD DAVID RANDOLPH      2507-40072
$IBFTC DKNAME  NODCK
1      DIMENSION DIFF(100),PDIFF(100)
2      DIMENSION RT(100),STR(100),RTLG(100),STRLG(100),ENP(100)
3      DIMENSION DENOM(100),CPRIM(100),F(100),FF(100),GAM(100),SLG(100)
4      DIMENSION GAMMA(100),SCAL(100),RLG(100),RRLG(100),R(100)
5      DIMENSION TRT(100),VMU(100)
6      100 FORMAT(4F10.6,I4)
7      101 FORMAT(F10.5,F10.2)
10     200 FORMAT(/3X,5HSHEAR,5X,5HSHEAR,5X,7HN PRIME,3X,7HK PRIME,5X,
15HGAMMA,3X,5HGAMMA,6X,5HSHEAR,4X,5HDIFF.,4X,7HPERCENT,5X,4HTRUE,3X
2,8HAPPARENT)
11     201 FORMAT(3X,6HSTRESS,4X,4HRATE,47X,6HSTRESS,11X,10HDIFFERENCE,3X,5HS
1HEAR,2X,9HVISCOUSITY)
12     202 FORMAT(64X,5HCALC.,25X,4HRATE,5X,5H(CPS))
13     203 FORMAT(F10.5,F10.2,F10.5,F10.6,F10.3,F10.3,F10.5,F10.6,F10.5,F10.2
1,F10.2)
14     204 FORMAT(4F10.6,I4)
15     5 READ(5,100)AA,BB,CC,DD,N
16     DO 1 I=1,N
17     READ(5,101)STR(I),RT(I)
20     1 CONTINUE
21     DO 7 I=1,N
22     RTLG(I)=ALOG(RT(I))
23     STRLG(I)=ALOG(STR(I))
24     RLG(I)=(RTLG(I))*(.30)
25     RRLG(I)=(RTLG(I))*(.20)
26     R(I)=RTLG(I)
27     ENP(I)=(AA)*(.30)*(RRLG(I))+(BB)*(R(I))*(.20)+CC
30     DENOM(I)=(RT(I))*ENP(I)
31     CPRIM(I)=STR(I)/DENOM(I)
32     F(I)=ENP(I)-(1.0)
33     FF(I)=(8.0)*F(I)
34     GAM(I)=(32.17)*(CPRIM(I))*FF(I)
35     GAMMA(I)=(GAM(I))/(0.000672)
36     TRT(I) = ((3.0*ENP(I)+1.0)/(4.0*ENP(I)))*RT(I)
37     VMU(I) = (STR(I)/TRT(I))*47880.0
40     7 CONTINUE
41     DO 2 I=1,N
42     SLG(I)=(AA)*(RLG(I))+(BB)*(RRLG(I))+(CC)*(R(I))+DD
43     SCAL(I)=EXP(SLG(I))
44     DIFF(I)=STR(I)-SCAL(I)
45     PDIFF(I)=((DIFF(I))*(100.0))/(STR(I))
46     2 CONTINUE
47     WRITE(6,200)
50     WRITE(6,201)
51     WRITE(6,202)
52     DO 3 I=1,N
53     WRITE(6,203)STR(I),RT(I),ENP(I),CPRIM(I),GAM(I),GAMMA(I),SCAL(I),
10DIFF(I),PDIFF(I),TRT(I),VMU(I)
54     3 CONTINUE
55     WRITE(6,204)AA,BB,CC,DD,N
56     GO TO 5
57     END
$ENTRY

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VITA

Donald David Randolph

Candidate for the Degree of

Master of Science

Thesis: A CAPILLARY VISCOMETER FOR NON-NEWTONIAN LIQUIDS

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Biographical:

Personal Data: Born in New Martinsville, West Virginia,
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